Iceberg Water Transportation from Antarctica to Australia

Iceberg (credit Walk, 2000)

by Bruno SPANDONIDE

School of Geography and Environmental Studies

A thesis submitted in fulfilment of the requirements for the PhD Degree
at the University of Tasmania, April 2012

Declaration of Originality

This thesis contains no material which has been accepted for the award of any other degree or diploma in any tertiary institution, and to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Signed

Bruno SPANDONIDE

25 April 2012

Annotation

This thesis is an uncorrected text as submitted for examination.

Abstract

The amount of iceberg water that annually dissolves into the sea corresponds to a substantial part of the world's annual consumption of freshwater. The Australian Antarctic Territory (AAT) has 30 % of the icebergs of the world. This freshwater resource melts into the Southern Ocean. If harvested, it will have a positive effect on terrestrial ecosystems and the water market. This renewable freshwater resource will need a sustainable transportation system. The south western corner of Australia is drought prone and freshwater availability is a limiting factor. Western Australia (WA) and Perth are facing water problems. The demand and requirement for water is increasing. Australian freshwater supplies could be increased using this type of freshwater resource with appropriate technology. The question of whether icebergs from Antarctica could be transported to help solve this water shortage was studied in the 1970s and given up later because of economic and environmental obstacles. The questions need to be examined as to what are the most appropriate transportation techniques, how marine ecosystems could be protected and if a profitable system of transportation can be designed. The aims and objectives of this research are to study the geographical transportation conditions and to determine the feasibility of an iceberg transportation system from the AAT to WA. It will propose future iceberg transportation research. I studied and analysed iceberg properties, iceberg detection, sea transportation systems and techniques, environmental issues and the protection of marine ecosystems, and legal considerations related to the transportation of iceberg freshwater and the profitability of a specific iceberg water transportation system between the AAT and WA. My work provided a paradigmatic frame for iceberg transportation research. It is an original contribution to the water transportation discipline. Within this frame, a new design for an iceberg transportation system was proposed. Practical and feasible technical parameters of the iceberg transportation system were developed. The transportation system is based on three main steps:

1. belting and wrapping of the iceberg in-situ with a bag and a collar;
2. transportation of this system into warmer areas and the collection of the melted water of the iceberg in the collar and specific fresh waterbags, and
3. waterbag transportation from Antarctica to Australia using sustainable techniques of current drifting and kite towing.

Given the increasing challenges for water in south WA this iceberg transportation system, could represent a viable long term source of freshwater. This iceberg transportation system proposal is an innovation which may be used by the Australian Government or private companies in further research to provide solutions for the freshwater crisis.

Statement of Authority of Access

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25 April 2012

Statement of publication

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The work for my thesis was also an extraordinary opportunity to discover the natural splendours of Tasmania

Bruno Spandonide

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Chapter 1 Introduction

Figure 1.0 Iceberg Vodka (credit Iceberg Vodka[1], 2007 n.p.)

> There is only one source which can decrease the amount of human efforts, called in the modern style of phrasing, work rationalisation.
> (Translated from Weil, 1935 p. 28)

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[1] http://www.icebergvodka.com/enter.htm

Chapter 1 Introduction

1.1 Area of Research

Iceberg transportation research belongs to the general field of transportation geography. Geography is the spatial study of natural and human facts (Pattison, 1990). Transportation uses a variety of infrastructure and means in order to create a movement of both goods and people (Rodrigue, Comtois and Slack, 2009[2]). Over the last century transportation has become a critical element in the workings of contemporary societies and the expansion of global economies. Economic activities spatial distribution depends on technical processes and resources sites. Transportation routes are based on the principle that resources are not distributed equally in the world (Rodrigue, 2009). These types of transportation bring with them a variety of strategic operating infrastructures that have a diversity of economic and social functions.

According to Rodrigue (2009 n.p.[3]):

> Traditionally, transportation has been an important factor behind the economic representations of the geographic space, namely in terms of the location of economic activities and the monetary costs of distance.

However, beginning in the 20th century transportation and geography were increasingly understood to be in dynamic interaction, as transportation constitutes the basis of complex spatial systems and geography seeks to explain spatial relationships based on transportation. As a result, after the Second World War, transportation geography became a discipline on its own. Geography of transportation investigates spatial phenomena of natural and human movements. It is concerned with the spatial constraints, the locations, the physical characteristics, the techniques and the objectives of movements. Geographical structures, energy resources, transportation modes and infrastructures, routes and travel time are the main areas of research in transportation geography. Increasingly, attention is also directed towards understanding the interlinked relations between transportation systems and their engineering, socioeconomic, cultural, legal, environmental and political aspects.

[2] http://people.hofstra.edu/geotrans/index.html
[3] http://people.hofstra.edu/geotrans/eng/ch1en/conc1en/ch1c1en.html

1.1.1 Background

Freshwater is delivered to consumers via a variety of operating systems and transportation techniques. Water transportation is a major challenge for the 21^{st} century as global populations increase, and demand for freshwater escalates (Organisation for Economic Co-operation and Development, OECD, 2009; see also Appendix 1). Available resources are under pressure as the development of new water-consuming activities becomes more widespread (Falkenmark, 1994). Western standards of water use are now widely adopted throughout many parts of the world, and many other parts aspire to those standards. Traditional water supplies are under pressure and traditional transporting methods are increasingly considered to be inadequate and unsustainable; as a result it is anticipated that in this context the supply costs and prices of freshwater may increase (Rodrigue, 2009). Clarke (1993) and Gleick (1993, 1999) claim that even in the best scenarios water shortage will reach a peak by 2050, largely affecting arid and overpopulated countries. Improvements in existing systems of water management will continue to be an essential part in meeting the growing demand for water (Drouart, 1999; James *et al.*, 2003; Vandana, 2003). However, novel alternatives also need to be examined. Alternatives types of freshwater supplying technologies must be considered to provide a more sustainable water accessibility.

1.1.2 Scientific Interest

The possibility of utilising icebergs to provide freshwater has been researched for over 30 years. The idea that icebergs might be transported to water scarcity regions was first studied by Isaac in the late 1950s (Husseiny, 1978; de Villiers, 2000). A few years later Weeks and Campbell (1973) and Hult and Ostrander (1973) explored the possibility of using icebergs to supply the temperate zones of the Northern Hemisphere with freshwater. However, attention turned to the Southern Hemisphere, when in 1977 the government of Saudi Arabia commissioned the French explorer Victor to tow an iceberg from Antarctica to Saudi Arabia. Delegates to the First International Conference on Iceberg Utilisation, held in Ames, Iowa in 1977, argued that icebergs were a potential supply of freshwater (Husseiny, 1978). Antarctic icebergs were identified as a realistic source for freshwater but a specific project was never formally undertaken. Conference attendees concluded that, in the short term, operations associated with iceberg utilisation were too costly and unreliable. Indeed, all early iceberg transportation projects were understood as having failed because of financial and technological difficulties.

As a result, research into iceberg utilisation slowed considerably. Few significant practical experiments were undertaken.

In the 1990s increased attention focused on waterbag transportation as maritime water transportation surpassed other types in terms of cost efficiency. The first industrial scale experiments using waterbags for liquid freshwater transportation were successful. For instance, the Spragg waterbag company developed a system of marine train transporters composed of a system of bags, zippers, and a tugboat (Spragg, 2006). The Medusabag Company designed a 100,000t prototype bag as a precursor to larger bags made with large flexible fabric barges (Medusa, 2006). These experiments raised the possibility of using waterbags to transport icebergs (Spandonide, 2004). These bags are not yet designed for iceberg transportation; but as a technique they represent a potential solution to some of the difficulties of transporting icebergs (Schwerdtfeger, 1986).

An example of the limits of traditional freshwater availability can be found in Australia, which is the world's driest continent after Antarctica with three-quarters of the land described as arid or semi-arid. As the sixth largest country in the world, Australian freshwater resources are around 300 km^3/year. With 250 km^3 classified in runoff water, there is little freshwater reserves in the form of lakes and rivers. Importantly the distribution of runoff is not uniform. It varies between 0.4% in the desert to 60% in the tropical north where only a tiny fraction of Australia's total population live (Chartres and Williams, 2005). Figure 1.1a and b present the average percentages of runoff in Australia (NLWR[4], 2002).

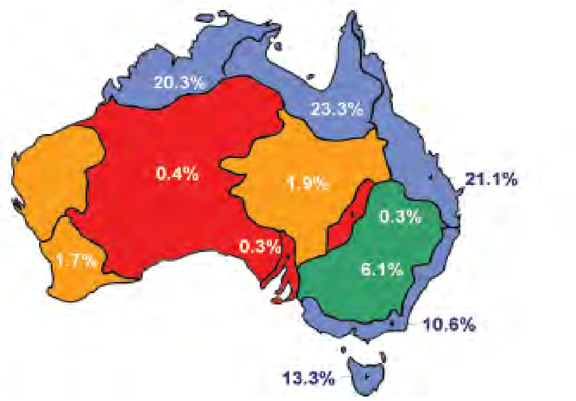


Figure 1.1a Australia's Distribution of Runoff (credit Water and the Australian Economy, 1999 from National Land and Water Resources 2001, p. 24[5]; Chartres and Williams, 2006[6] p. 18)

[4]http://www.anra.gov.au/topics/agriculture/pubs/national/agriculture_landscape.html 2002
[5]http://www.watermarkaustralia.org.au/watermark_pdf/version2/Part%201/7bp_surfacewater.pdf

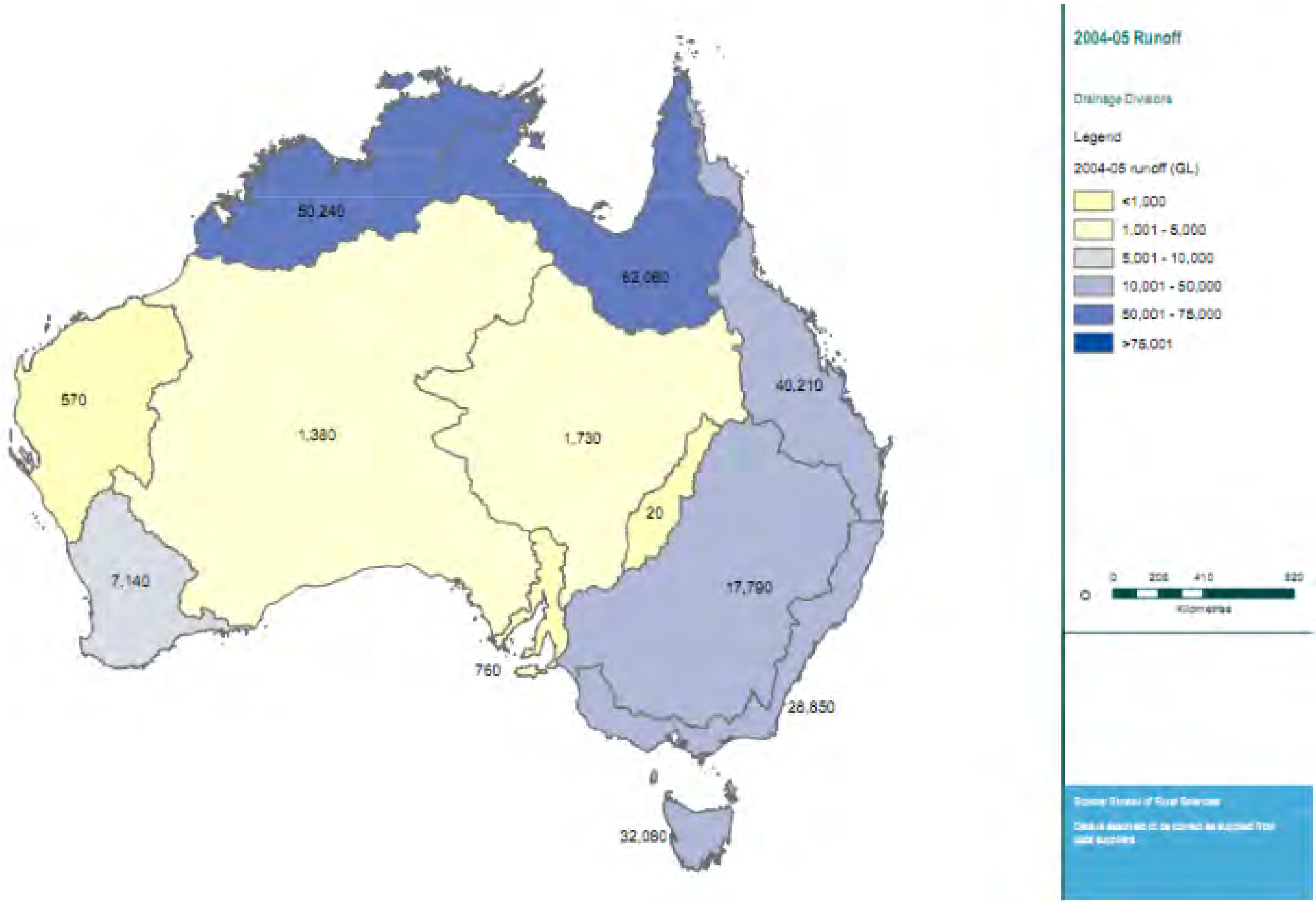


Figure 1.1b Australia's Annual Average Distribution of Runoff from Each Drainage Division in 2004-05 (credit Bureau of Rural Sciences 2005[7] n.p.)

Seventy-five percent of Australians live in urban areas of the eastern and the south-eastern coastal regions of the continent where water supports economic growth and development. However, extensive water resources are not located in these areas. Furthermore, since 1997, rainfall has been below average across much of southwest and southeast Australia. This means that the temperate crowded zone in the southeast suffers from water scarcity and is affected by declining rainfall. Several regions are severely affected by continuing droughts and desertification in Queensland, New South Wales, Northern Territory, Victoria and Western Australia (WA) where, climate change could have severe effects on ecosystems, economic activities and public health (Garnaut Climate Change Review, 2008[8]).

[6] http://www.wentworthgroup.org/docs/Chartres_&_Williams.pdf
[7] http://www.water.gov.au/WaterAvailability/WhatIsOurTotalWaterResource/Runoff/index.aspx?Menu=Level1_3_1_5
[8] http://www.garnautreview.org.au

According to the AGNWC[9] the total water use in Australia was around 80 km^3 in 2005 and 75% of this water returns to the environment (Australian Government NWC, 2007). Consumptive use of water in the Australian economy was under 20 km^3. Household water use is around 103,000 l/person/year, or 282 l/capita/day and represents 10% of the total consumption, or about 2 km^3 (Australian Government NWC, 2007). According to the Wentworth Group (2006), water supply in Australia is a critical political, social, economic and environmental issue. Indeed, the growing difficulties in sourcing sustainable supplies of freshwater and the increasing demand for freshwater to support current and future levels of economic growth is a pivotal part of the present environmental crisis (Lindenmayer, 2007).

The long-term effects of a reduction in the availability of freshwater are apparent in the crowded southwest corner of Western Australia (WA). According to the WA water agency (2007 p. 8[10]) “Groundwater resources, the most important water resources in WA, are localised and fragmented, and water quality varies from fresh to hypersaline”.

Abundant groundwater resources exist in the north of the State[11]. However, they support rich ecosystems and the transportation of such a resource to the south would be costly. Eighteen percent of the State’s available groundwater had been allocated to their sustainable limit in 2000 (including saline groundwater) with about 39% of Perth Basin groundwater (Water WRC, 2000). According to the WRC[12] (2007 p.8) “surface water resources vary greatly across the State, with cyclonic-based river flow to the north, and mostly ephemeral stream flow to the south”. Thirty-eight percent of the WA’s surface water resources are already used beyond the levels of their long-term renewability limits. According to McFarlane[13] (2005, p. 13):

> For all surface waters in the southwest, the sustainable yield was estimated to be about 24% of the mean annual flow (WRC 2000). These figures could be interpreted as indicating that there remain abundant untapped resources. However, many of these resources have water quality or development aspects which limit their use or the water resources are located far from where they are needed. Therefore, it is not feasible for all water resources to be fully exploited.

[9] National Water Commission http://www.water.gov.au/WaterUse/index.aspx?Menu=Level1_5
[10] http://www.nwc.gov.au/resources/documents/WA-NWI-ImpPlan_PartA.pdf
[11] National Land & Water Resources Audit, NLWR http://www.anra.gov.au/topics/water/overview/wa/index.html
[12] Water and River Commission's http://www.nwc.gov.au/
[13] http://www.csiro.org/files/files/p3uh.pdf

Ecological Water Sustainable yields are calculated as a percentage of sustainable extraction levels avoiding damaging the environment compared to the mean annual flows (for rivers) or mean annual recharge (for aquifers).

In another example, McFarlane claimed that “most large rivers of WA originate in the State’s saline wheatbelt and are unsuitable for drinking or other uses (WRC, 2002a)”. In 2007 the Intergovernmental Panel on Climate Change (IPCC) highlighted that the capital city of WA, Perth, is under pressure to provide adequate freshwater for residential and commercial activities. Perth uses its aquifer as its main potable water resource. However, about 30 years ago Perth experienced a spectacular change of its climate resulting in a winter rainfall shortage (around 20% of decrease). Temperatures increasing rates and dryer winters affected durably the aquifer water levels.

In 2001 1.46 million people were living in the Greater Perth area (comprising Metropolitan Perth and the adjacent regions of Mandurah and Murray). It is anticipated that 1.99 million people will live in the region in 2021 and 2.22 million in 2031 (WAPC[14], 2004). The average water consumption by Perth residents is the highest in Australia and very high by world standards. The current demand forecast varies from 0.265 to 0.37 km^3/yr and by 2030 demand in the north metropolitan area is expected to have grown by 0.043 km^3 (55%), the south metropolitan area (including Mandurah) by 0.093 km^3 (37%) and the city of Perth by 0.05 km^3 (30%). According to McFarlane (2005, p. 17) “in 2000 total estimated water use had doubled during the previous 15 years and it was anticipated to double again in the next 20 years” (WA Department of Water Report, 2008). As a comparison, in WA, surface water use has grown by 0.24 km^3 (37%) and groundwater by 0.45 km^3 (40%) since 1997. The consumption of water in the Perth region could be around 0.5 km^3/year by 2050 (Figure 1.2 and Figure 1.3).

[14] Western Australian Planning Commission WAPC http://www.planning.wa.gov.au/

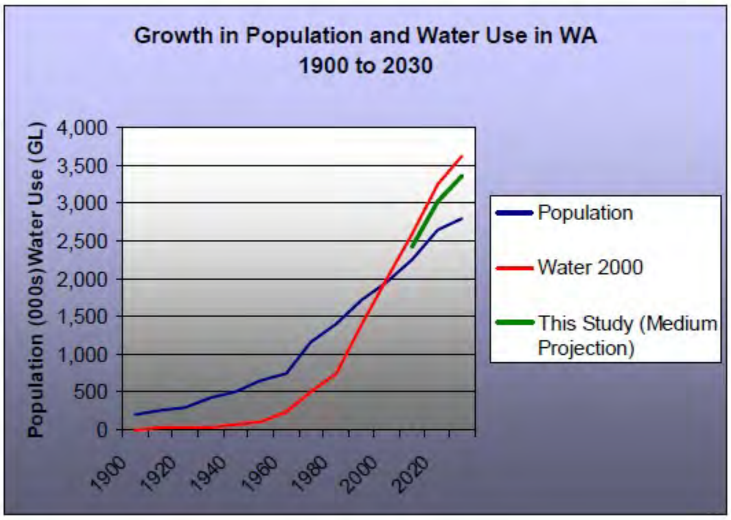


Figure 1.2 Growth in Population and Water in WA since 1900 (credit WA State Report[15], 2008 p. 36)

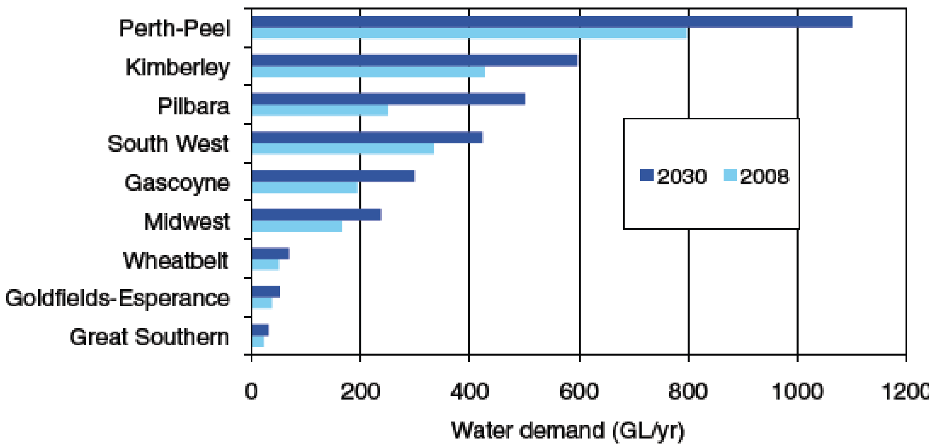


Figure 1.3 Regional Medium Demand Growth (credit WA Department of Water Report[16], 2010 p. 4)

In 2007 Flannery (2007 n.p.[17]) estimated that Perth could become an “abandoned city with no more water to sustain its population”. In response to water shortages the city of Perth has instigated water restrictions, which occur two days per week. Attempts to increase the amount of freshwater available have resulted in the construction of Perth’s first desalination plant (Figure 1.4).

[15] http://www.water.wa.gov.au/PublicationStore/first/90954.pdf
[16] http://www.water.wa.gov.au/PublicationStore/first/90953.pdf
[17] http://news.bbc.co.uk/2/hi/science/nature/6620919.stm

Figure 1.4 Perth Desalination Plant (credit Verbeek[18], 2007 p. 37)

The new plant produces 0.07 km^3/year for a construction cost of AUD 387 million and a AUD 25 million running cost per year over 30 years. The desalination facility will produce a total of 2 km^3 of freshwater at a cost of AUD 1.2 billion over 30 years for a water demand of 15 km^3. Engineering projects such as desalination plants will continue to be important technical responses to WA's future freshwater demands as other options of water supply.

Antarctica has 60% of the world freshwater resources. Large Antarctic icebergs are located some 3,000 km south from Perth (Figure 1.5).

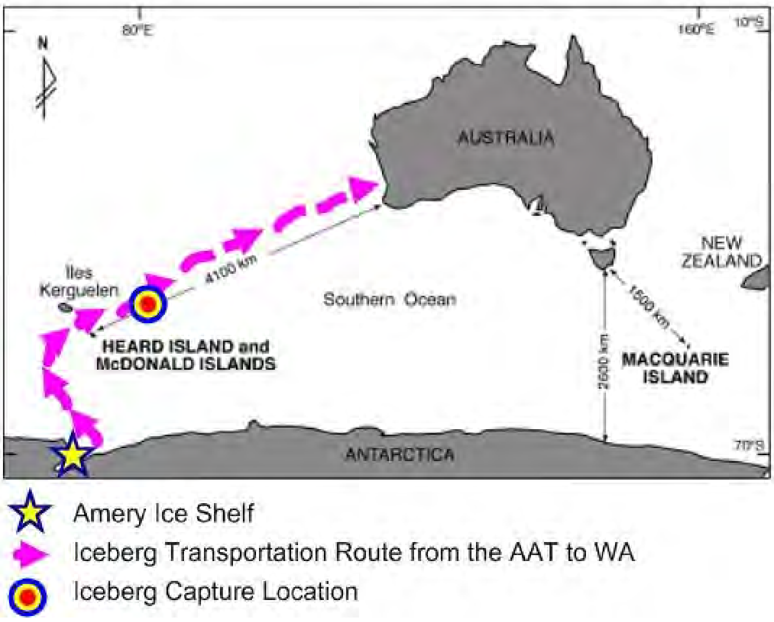


Figure 1.5 Tabular Icebergs are Located 3,000 km Southwest from Perth, WA (credit from Kriwoken *et al.*, 2007 p. 19)

[18] repository.tudelft.nl/assets/uuid:1272fd32-6a64-4ffe-882f.../Verbeek.pdf

Australia claims 42% of Antarctica (Figures 1.6).

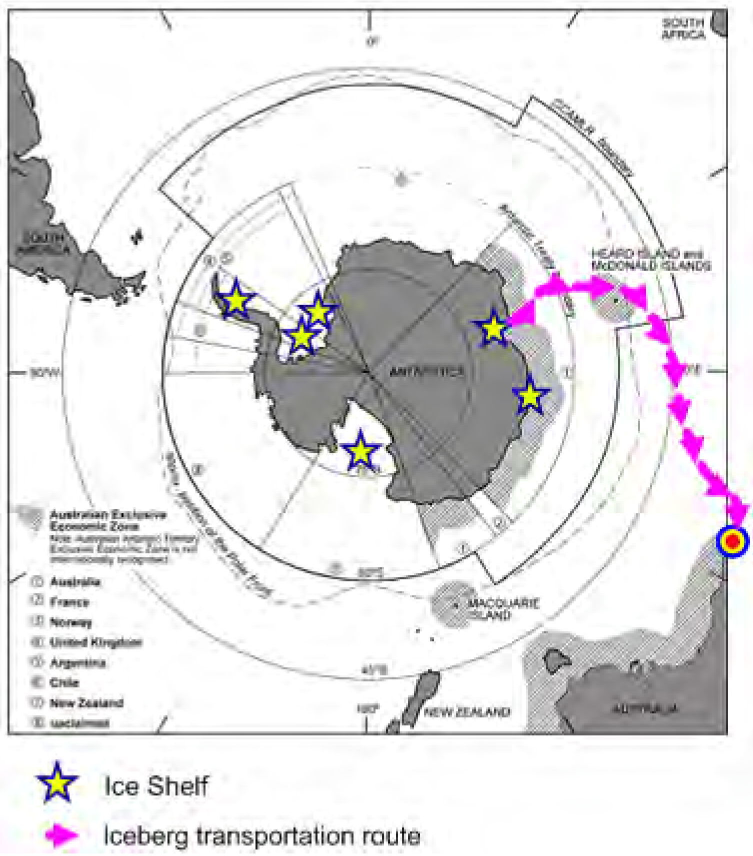


Figure 1.6 Antarctica, Australia Territorial Claim (credit from Kriwoken *et al.*, 2007 p. 108)

The icebergs found in the Australian Antarctic Territory (AAT) correspond to a potential water supply of 500 km^3/year with a sustainable yield of 100 km^3/year (Silva *et al.*, 2006). The AAT is located 2,825 km from WA and Australia is the closest country from Antarctica from 90^o E to 240^o E so the proximity of Antarctica to WA, combined with an increasing freshwater shortage, represents an opportunity to provide a sustainable medium to long-term freshwater iceberg resource.

The possibility of using icebergs to meet the increasing demand for water in WA requires a study of iceberg transportation and an assessment of the relevant technology for a transportation system from the AAT to Perth.

Institutional research is not yet studying iceberg transportation. Since the 1970s the Australian Antarctic Division (AAD) have undertaken extensive polar Antarctic research, yet research into the possibility of iceberg transportation focusing on movement between the AAT and Australia has been individual and sporadic (Senate Standing Committee on National Resources, 1984 p. 629). Research that has been conducted has not been brought together with relevant studies from other parts of the world. Existing disparate studies need to be collated together and there is also a need to undertake a study that can provide an update. A question underlying this thesis is why iceberg transportation has not previously been studied and promoted as a source of freshwater supply to Western Australia? Transportation geography can help to provide a new critical viewpoint on this problem. Transportation geography is less concerned with testing theories and more interested in using a range of multi-disciplinary perspectives and tools to study practical questions and alternative solutions. While the vast majority of studies in transportation geography have been focused on urban transportation systems, there are many advantages in utilising the insights gained from these studies and applying them to the possibility of iceberg transportation.

1.2 Research Aims and Objectives

Previous studies of towing icebergs from the AAT to WA have not been fully developed. However, WA is relatively close to Antarctica and could benefit from new sustainable systems of iceberg transportation. Given the dire consequences of a lack of freshwater for Perth and recent advances in water transportation, there is a strong incentive to evaluate the feasibility of iceberg transportation from Antarctic to WA.

The overall aim of this research is to examine whether transporting icebergs from the AAT to WA for freshwater is a technically and economically feasible and sustainable exercise.

In order to fulfil this aim there are a number of specific study objectives:

1. describe the physical and environmental characteristics of icebergs;
2. critically analyse the issues related to previous iceberg transportation systems;
3. study the technical operational conditions of a proposed route from the AAT to Perth;
4. analyse the political and legal consequences of an iceberg transportation system in the international and domestic context;
5. undertake an economic cost benefit evaluation of an iceberg transportation system from the AAT to WA.

Given the range of these objectives, it is apparent that research into iceberg transportation requires a multidisciplinary research approach. The field of transportation geography is well-suited to providing the analytical tools necessary to explore the natural, environmental, technical, economic, political and legal aspects of iceberg transportation.

The published scientific data on iceberg transportation is sparse and the subject is not well theorised. A description of the characteristics of previous projects directed towards iceberg transportation provides a context within which to assess an iceberg water transportation system specifically adapted for transportation from the AAT to Perth. In order to evaluate its feasibility an initial cost analysis needs to be undertaken to assess the level of long-term operating costs. This study could open new possibilities for further practical experiments and new investigations.

1.3 Methods

According to Rodrigue (2009) “transportation is not a science, but a field of inquiry and application”. Geography is a human science. Transportation geography is both a theoretical and practical field as parts of its academic inquiry. As an applied human science, transport geography is based on empirical data, analytic techniques, specific methods and theories. These academic tools range from simple descriptive measures to more complex modelling structures constituting a conceptual background for transportation systems analyses and practical strategies aimed at improving the efficiency of movement by identifying spatial constraints to transportation. Transport systems can be conceptualised and modelled as sets of relationships between different demands, nodes and networks (Figure 1.7).

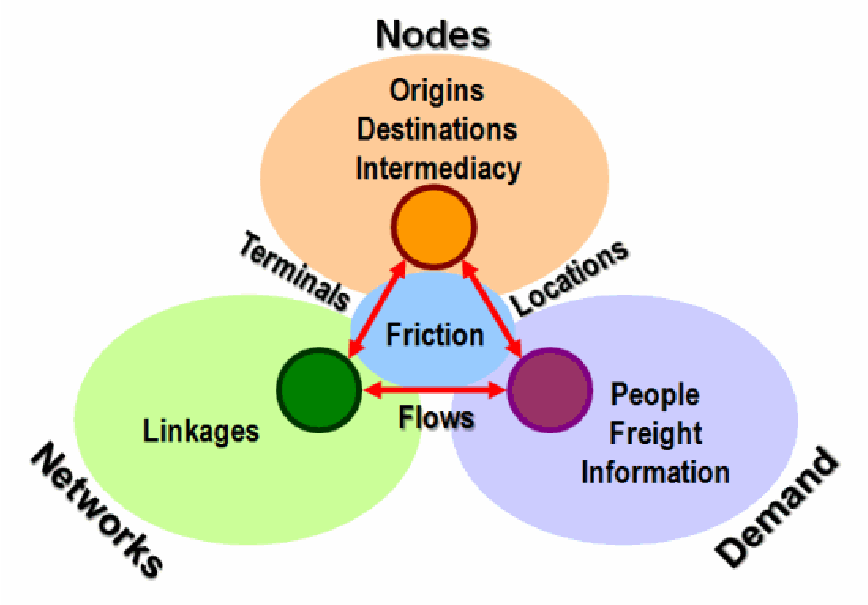


Figure 1.7 Demand, Node and Network: the Transportation System (credit Rodrigue, Comtois and Slack, 2009 p. 7[19])

According to Rodrigue, Comtois and Slack (2009 n.p.[20]), "demand for the movement of people, freight and information is a derived function of a variety of socioeconomic activities". The level of spatial accumulation of socioeconomic activities jointly defines demand and where this demand is taking place (the location of the demand). Nodes are the locations where movements start, finish and are transferred. Node service demand and their accessibility define their capacity. They range from local to global scales. The links between the nodes compose the transportation networks represented by transport infrastructure. The flows of transportation are the amount of traffic over the networks (a function of the demand and the capacity of the linkages to support them). They are subject to the friction of distance (impedance). Distance and nodes accessibility are the most significant factors.

Transportation systems are represented by models of growing complexity according to their characteristics in terms of distances, accessibility, spatial interaction, and transportation modes. In the case of iceberg water transportation from the AAT to WA, nodes, flows and modes can be addressed through transportation analysis. Rodrigue's work in transportation geography represents a valuable contribution to the theoretical framework which can be applied for practical research. The methodology of this thesis is based on the research

[19] http://people.hofstra.edu/geotrans/eng/ch1en/conc1en/trspsystem.html
[20] http://people.hofstra.edu/geotrans/eng/ch1en/conc1en/trspsystem.html

principles of Rodrigue (2009). Transportation studies are interdisciplinary. They concern geographical, engineering, legal economic and planning issues, (Hoyle and Smith, 1998) and rely on methodologies often developed by other disciplines such as engineering science, planning, history, politics, economics, social and environmental sciences (Figure 1.8).

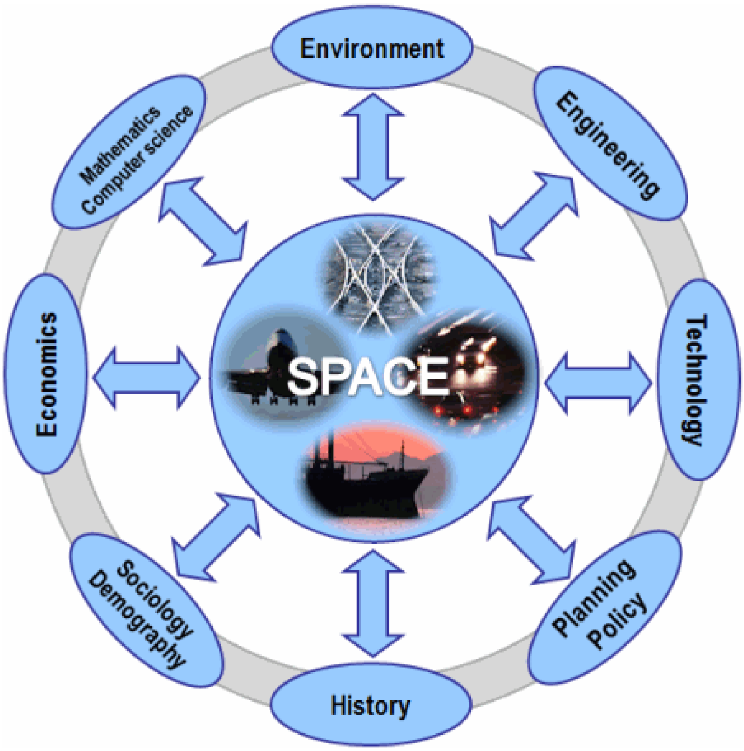


Figure 1.8 Transportation Conceptual Frameworks (credit Rodrigue, 2009 from Hoyle and Smith, 1998 p. 17[21])

Historical transportation geography studies the spatial, natural human long-term evolutions of transportation systems characteristics. This includes the historic changes within an area brought about by transportation technologies and the circumstances and environment from which originate transportation systems, with technical, socio-economic, cultural and political perspectives. Transportation engineering focuses on the physical and mathematical aspects of transport systems and the construction and maintenance of transportation infrastructure. Technical engineering studies of transportation systems are based on scientific analyses, such as spatial interaction models, operations research, and optimisation of the distribution and scheduling of transportation resources. According to Rodrigue (2009 p. 5):

[21] http://people.hofstra.edu/geotrans/eng/ch1en/conc1en/dimensiontransp.html

> [t]he technological dimension of transportation is not necessarily a field of study but a consideration of technological change on transportation systems. It is mainly concerned about the efficiency of infrastructures, modes and motive forces. Successive innovations have brought forward new distribution systems whereas others have become obsolete and disappeared.

It is possible to assess technological performances in technical and economical terms. Economic transportation geography assesses the transport demand by different sectors of activity and evaluates the features of transportation modes through economic standards.

According to Rodrigue (2009), transport demand is a function of the nature and the importance of economic activities and of modal preferences (Kansky, 1963). Therefore the demand for transport is reflected by transportation systems in terms of transport network structures, and services production. Transportation systems are direct functions of vehicle characteristics (functions, plans, materials, dimensions, operations and life expectancies). Transportation systems are determined by technological development, the locations and uses of the resources they carry, the costs of the infrastructure, the maintenance costs and the distance they are able to cover.

According to Rodrigue, Comtois and Slack (2009 n.p.[22]), "[E]nergy is the potential that allows movement and/or modification of matter". Establishing, operating and running transportation activities implies spending energy: the extraction, processing and transportation of resources involve the use of energy (Chapman, 1989). Energy accounts for a large part of transportation costs and causes important variations in the composition of freight transport demand between countries. Transport supply costs account for the majority of the overall costs of a natural resource and are composed of the costs of the infrastructure and of the transportation service which are based on energy costs and maintenance activities costs (Boyle, 2003). According to Rodrigue, Comtois and Slack (2009[23]):

> Energy exists in various forms, including mechanical, thermal, chemical, electrical, radiant, and atomic and are all inter-convertible. Forms of energy come from sources defined as renewable and non-renewable, which include chemical reactions (mainly combustion), nuclear reactions (fission), the effect of gravity (mainly hydraulic) and direct (photovoltaic) and indirect (photosynthesis and wind) solar energy conversion.

[22] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/ch8c2en.html
[23] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/energysrc.html

Fossil fuels can be based on petroleum, natural gas coal, or wood products. Renewable energies comprise power derived from solar radiation, wind, water, geothermic, animal and human power. According to Rodrigue, Comtois and Slack (2009 n.p.[24]), "[M]any of these reserves cannot be exploited at reasonable costs ... or are unevenly distributed around the world". The world's power consumption is about 18 terawatts/year and 86% is obtained from fossil fuels (15.5 TW) (Lenzen, Dey and Hamilton, 2003; Rodrigue, Comtois and Slack, 2009).

Transportation now accounts for around 20% of all the energy being consumed (3.6 TW). The increase of petroleum fuel demands is correlated with the increase of transportation demand (Figure 1.9).

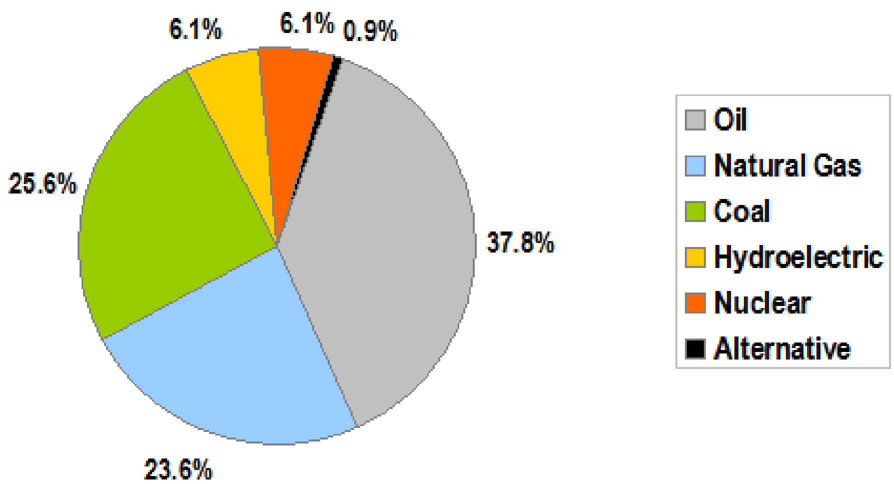


Figure 1.9 World Energy Production (credit Energy Information Agency, 2006 in Rodrigue, Comtois and Slack 2009 n.p.[25])

In the case of water transportation, the nature of the good determines the specificity of operating conditions: water is a liquid substance which flows, evaporates, seeps and freezes and which is difficult to measure and identify under all possible physical states. According to the transportation costs method, the accessibility and availability of water determines its cost. The water transportation cost for particular uses depends on its location, quality and timing (McCalla, 1994). The water state and its location determine its accessibility. There are important inequalities over its accessibility. As noted by the Food and Agriculture

[24] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/ch8c2en.html
[25] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/worldenergyproduction.html

Organisation (FAO), the duration of the accessibility of water governs its renewability (FAO, 1995). The offer depends on natural aspect. The energy cost in water economy is generally conditioned by access to the resource, the nature of the resource operation and the distance of transportation. For water movement, the transfer costs are related to operation and maintenance costs.

According to the Environmental Protection Agency (EPA), only 1% of the Earth's fresh water is of such a quality and in accessible locations to be acceptable for human consumption (EPA, 1997). Increasing demand for freshwater resulting from an increased global population makes available water supplies inadequate. Therefore new demands require new allocation systems. Two conditions are necessary for the optimal transfer of water:

1. the transfer is the least cost alternative, which can exceed its value because of socio-economic inequalities;
2. the benefits exceed the losses, a condition that is exaggerated in emergency situations.

Cost benefits analyses are therefore an efficient method to evaluate water transportation systems.

Practitioners within the environmental sciences examine the environmental impacts of transportation systems and the interactions between transport operations and environmental conditions, such as topography, climate and ecosystems. Of particular relevance for this thesis are studies that examine the externalities (for example, the use of natural resources and pollution) that various modes of transportation impose on the environment.

A political science approach to transportation is concerned with examining relations between political power (whether governmental or corporations) and transportation. Studies may include inquiries into governmental control over the transportation process, the allocation of transportation resources and historical studies of transportation system planning, within corporations and governments and their intervention strategies.

Sociological studies within transportation geography analyse transit networks social interactions on and around, modal and spatial social choices affecting transportation distance. Sociological analyses of transportation are interested in exploring issues concerned with the social aspects of systems of transportation, the types of services provided by transport suppliers, the demographic attributes of users, the social costs of transportation systems and issues of safety and risk associated with transportation.

Interdisciplinary research is theoretically and conceptually complicated, with multiple obstacles in practice (Haggett and Chorley, 1969). The field of transportation geography is at the intersection of several concepts and methods initially developed outside the discipline that have been adapted to its particular interests and concerns (Haggett, 2001).

A multidisciplinary approach, such as is provided by transportation geography, is required to study iceberg transportation as the movement of massive chunks of ice touches on many different areas of expertise and scholarship. Iceberg transport involves many facets of knowledge including interfaces of geography, physics, environmental science, water and marine transportation technical engineering, social sciences, economy and law (Figure 1.10).

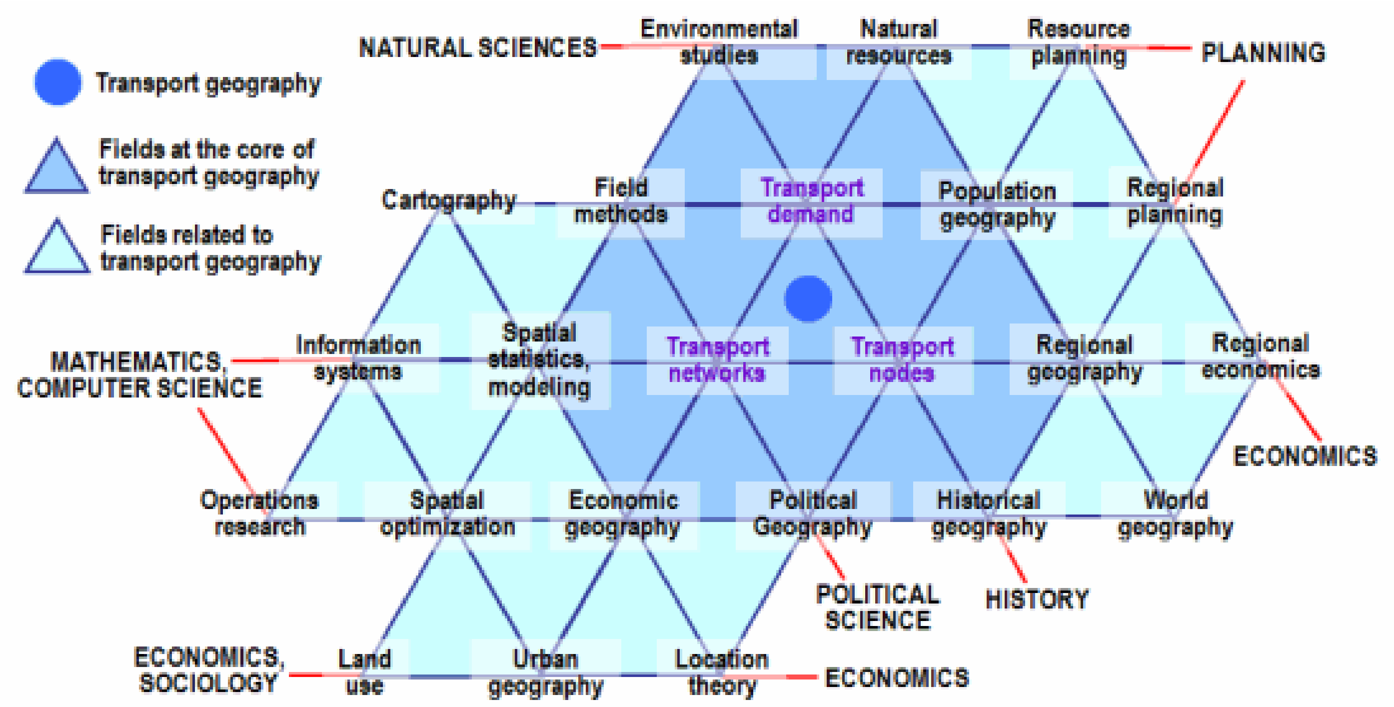


Figure 1.10 Geography Multiple Approaches: A Modern Synthesis (credit Rodrigue, 2009 from Haggett, 2001 n.p.[26])

[26] http://people.hofstra.edu/geotrans/eng/ch1en/conc1en/fieldstransp.html

1.4 Organisation of the Research

The first research task was to coherently formulate and framework the research questions that I was interested in addressing. Working within the field of transportation geography I chose theoretical and conceptual aspects of iceberg transportation for study, including the physics of ice, remote sensing sciences, environmental sciences, maritime sciences, geopolitics. In particular I organised my key questions in terms of the following research themes: for geography, water demand in WA, the physical and chemical characteristics of icebergs, a study of previous iceberg transportation projects, for maritime sciences, relevant maritime technologies; for environmental sciences, impacts assessments of iceberg transportation; and for international law, legal concepts relevant to iceberg transportation. Using these specific research paradigms allowed me to elaborate a research program and to tie together the theoretical framework and empirical evidence. These fields of research are important to the scope of the thesis, constituting the basis for the development of a theoretical frame, and a project design that can answer these questions.

The research questions were directly interrelated. A comprehensive review of the literature of iceberg transportation projects was conducted in order to investigate and describe problems associated with iceberg transportation using an accumulative method covering geographical, historical, technical, environmental and legal categories. To design a transportation system for icebergs transportation several specific points have to be investigated including:

- evaluating the need for iceberg water supply in Australia and in the world;
- studying the physical and environmental characteristics of icebergs;
- analysing specific aspects of iceberg transportation geography (towing techniques, winds, currents, timetable);
- answering questions about why previous iceberg transportation projects failed;
- assessing how earlier and new techniques of maritime transportation could be specifically adapted for iceberg transportation;
- determining how the institutional framework within the Antarctic Treaty System (ATS), maritime transport and environmental law are interconnected.

In order to develop a conceptual understanding of the overall thesis topic I collected data to help answer theoretical research questions and explored empirical data and case studies of iceberg transportation. Empirical evidence was gained from earlier studies and projects and from a range of literature. The literature was systematically analysed according to the requirements presented by each discrete research agenda. A practical conceptual framework was designed to analyse iceberg transportation issues. The multiple issues incorporated within the conceptual framework of iceberg transportation allowed for a wide range of interconnected interpretive practices.

Then the research focused on the analysis of the empirical materials that deal with the movement of icebergs including technical study, engineering studies, business reports, manufacturing models, experimental protocols, project case studies, equipment advertising and patents or industrial design). This provided a specific perspective of the research able to match the research questions previously drawn. I was able to elaborate research assumptions on the potential of a renewable energy based iceberg water transportation system. The related cost benefit analysis indicated the potential economic viability of an iceberg water transportation system. Specific analyses of iceberg transportation systems have never previously been undertaken and reported in the field of Transportation Geography. Substantive conceptual material emerged from the data throughout the research process.

Throughout my research, the continuous interplay between the theoretical framework and data collection and analysis gave rise to new concepts with suggestions for practical applications. Throughout the research process, new insights were constantly added. As my project developed, I was able to identify and formulate several new research themes and issues for future study, none of which has previously been identified. New information was sought after and analysed in conjunction with the new themes and unanticipated issues.

The research process was exploratory and qualitative in nature, utilising a mostly inductive method (Hoyle and Knowles, 1998). As a geographical transportation system, iceberg transportation is suited to inductive research design that allows the research to guide the specific technical propositions. The major concept-building research processes and qualitative analytical methods were compared to the cross-disciplinary concepts and theory within the literature (Kvale, 1996). Data collection and analysis took place together, in an iterative manner as the analyses and assumptions suggested new areas of research. The recurrence of particular concepts within and between different areas of research highlighted the importance of critical elements to the iceberg transportation systems and the iceberg operation techniques. Analytic concepts provided by the field of transportation geography allowed the identification and assimilation of empirical information. Conceptual interpolations about the facts and figures of the origins and the causes of previous iceberg transportation issues gave a global insight into the requirements of a viable iceberg water.

I critically examined and compared a number of previous studies concerned with iceberg transportation to evaluate their strength and weaknesses. Of interest here were the factors of capacity and resilience in the case studies evaluating them and putting them in perspective with each others. Technical aspects of iceberg transportation were structured into specific categories to reach a degree of applicability (the practical side of the technical research is appropriate to be applied to further testing) matching the optimisation for iceberg transportation system case studies. I analysed with transportation geography tools the previous projects, identified the missing technical aspects and filled the conceptual gaps with concepts extracted from research on new technologies available such as waterbag characteristics, melted water collection techniques, and waterbag transoceanic transportation techniques (towing, sailing). I studied optimal iceberg accessibility and deterioration characteristics in ocean conditions found between the AAT and Australia. Furthermore, I then used these insights to critically extrapolate assumptions on which a model to optimise a system of iceberg transportation from the AAT to Perth was designed. I used map-making, technical drawing, planning and economics tools to define the location of the transportation route and the transit structure.

Based on these same assumptions I was then able to define an integrated sustainability strategy and design a new project proposal which could be economically and environmentally evaluated.

Eventually, the internal validity and conceptual level of the transportation research grew. In the end, I was able to answer the research questions and to assess generalisations and transferability of the assumptions systematising the parameters of the research. Caution regarding the application of the hypotheses and findings to a broad context should be applied, depending on the empirical similarity between case study contexts.

Cross-examination between the established academic themes and the data from the literature was used to provide a validation of the analysis. After explaining the problems and proposing solutions, the validation of these hypotheses and proposals includes: designing specific technical evaluations, modelling resource allocation models, suggesting models of environmental impact assessment and Geographic Information Systems (GIS), engineering, risk assessments analysis and policy analysis. The validation process confirmed and generalised the outcomes of an emergent project research for Australia. Transportation geography methods were used in the past and are not assessed as they are more limited to practical research than a theoretical science.

1.5 Limitations

The field of transportation geography provides a multidisciplinary perspective to study the myriad aspects of iceberg transportation. There are a number of limitations associated with the transportation geography scope of this thesis.

The very nature of the topic implies that there are not a lot of empirical data available concerning iceberg transportation experiments. A lot of articles and documents were published in the 1970s and were hard to access to. Some documents are also confidential because of the development stage of this research topic. Specifically, physical engineering studies of iceberg transportation techniques were not conducted for this thesis, though a series of possible experimental work has been suggested (Appendix 6). It was not possible to undertake practical experiments because of the restricted geographical scope of the PhD, confidentiality issues, unforeseen circumstances, and the lack of research coordination, engineering knowledge and technical support; it was decided to focus on other research objectives.

As the research has been discontinuous, some scientific areas, technologies, methods and even units have changed. This was particularly the case for the comparisons of cost analyses of iceberg transportation projects.

Coming from a non-English speaking background, scientific language requirements for a PhD thesis were challenging. Language accuracy was tested with the Flesch/Flesch–Kincaid readability tests designed to indicate comprehension difficulty of contemporary academic English. The two tests use word length and sentence length with weighting factors (Si and Callan, 2001). To simplify some passages the Fog index was also used.

1.6 Materials

The literature review of iceberg transportation was based on published articles and theses in fields such as geography of transportation, human geography, environmental sciences, remote sensing, maritime sciences and international law. I used the databases and journal resources of the Library of the University of Tasmania and the Australian Antarctic Division (AAD) library, and extracted information. For the physical and environmental conditions for icebergs, environmental sciences information, and the oceanic conditions found between the AAT and WA, or the technology used in remote sensing, I searched relevant and significant academic journals and publications (*the Annals of Glaciology, Antarctic Science, the Australian Antarctic Magazine, Desalination, Environmental Science and Technology Journal, The Georgia Engineer, Ice, the International Journal of Geographical Information, the International Transport Journal, the Journal of Advanced Transportation, the Journal of Environmental Engineering, the Journal of Geographical Systems, the Journal of Glaciology, the Journal of Transportation Engineering, Nature, The Naval Architect, Polar Research, Polar Record, the Polar Times, Population Space and Place, Science, Science of Ships and the Sea, Sustainable Development, the Transportation Journal, Transportation Law Journal, Transportation Planning and Technology, Transportation Review, Water and Environment Journal, Water Policy, Water Science and Technology, Water Supply*).

For the conceptual framework of the thesis I used the transportation geography methodology described by Rodrigue, Comtois and Slack (2009).

For the history of iceberg transportation, (winds, currents, timetable), the literature review was based on technical reports of previous iceberg transportation projects, such as the proceedings of the first International Iceberg Utilisation Conference and articles on previous projects. I extracted data on previous iceberg transportation, iceberg accessibility and iceberg deterioration.

For maritime sciences studies I used information from the specialised paper and electronic publications of the Canadian National Research Council, waterbag companies and kite companies. I extracted data on melted water collection, waterbag technology (skin, zipper, and bag equipment), bagging processes, transportation techniques (towing, sailing) and the sustainability of iceberg water transportation.

In order to assess the need, supply and demands for freshwater in Australia, and in the world, and international law I used official reports and specialised literature.

For the research about the legal aspects of iceberg transportation I used information from the ATS and the LOSC and the publications of Lundquist (1979), Joyner (1988), Francioni and Scovazzi (1997), Geon (1997), Ryland (1997) and Fallon and Kriwoken (2005).

1.7 Chapter Outline

The thesis is collated within 11 chapters which explore iceberg transportation. They are set out logically together as indicated below:

The first part aims to explain the iceberg properties that transportation systems have to consider. The first part of the research is related to physical and environmental characteristics of icebergs. This incorporates an analysis of the physical characteristics of ice (Chapter 2) and icebergs, their location, the production and concentration of icebergs (Chapter 3), the physical and biological environment within which icebergs are located and the geographical scales at which icebergs could be utilised (Chapter 4).

In the second part of the thesis an analysis of previous iceberg transportation projects is undertaken (Chapter 5) in order to determine what improvements could be made for future iceberg transportation projects.

The third part investigates elements of iceberg transportation (Chapter 6). I define the critical technical feasibility and environmental sustainability of future projects. The remote sensing tools that can assist in icebergs characterisation and the techniques that could be used for iceberg operation, transportation and distribution are described and discussed. The utilisation of waterbags, kites and currents are introduced as novel transportation technologies that could be used in future attempts at iceberg transportation.

The fourth part examines the technical aspects of iceberg transportation. I established research assumptions for the utilisation of icebergs as a freshwater resource and described a system model, studying the location of icebergs, enveloping methods, the process of operations, transportation and their routes (Chapter 7).

The fifth part investigates the feasibility of such a future project and the environmental (Chapter 8) legal and political (Chapter 9) and economic (Chapter 10) issues and requirements. The international and Australian domestic legal and political aspects of iceberg transportation are presented in an assessment of institutional complexities that determine how icebergs could be harvested, transported and ultimately used. The key steps would include critically examining how icebergs might be managed under the existing Antarctic Treaty System's legal regimes and describing the legislative and institutional arrangements regarding resource management, including maritime transport law and the political obstacles that iceberg utilisation faces and undertaking a cost benefit analysis of a new iceberg transportation system;

Overall, the profitability, economical feasibility and sustainability of a new iceberg transportation system are presented.

Chapter 2 Properties of Ice

Figure 2.0 Ice Crystals (credit modified from Bentley, 1902 n.p.[1])

[1] http://www.katyelliott.com/blog/2009/01/wilson-bentleys-snowflake-photographs.html
http://drawnassociation.net/2009/09/snowflakes-wilson-alwyn-bentley-1865-1931/

Chapter 2 Properties of Ice

The objective of this chapter is to describe the physical characteristics of ice in order to provide a broad context for the properties of icebergs, the construction and the maintenance of iceberg transportation operations and infrastructures. Water and ice are unique elements. The study of the physical and chemical behaviours of ice, its structures and technical properties such as sensing properties, melting and stability, is an important first step in understanding iceberg transportation. The properties of ice depend largely on the structure of its constituent water molecules which, in turn, determine the crystal structures for ice and how they can deform or rearrange.

The first part of this chapter describes the ice I_h (the ice in everyday life is known as ice I_h) and its physical, thermal, mechanical, electrical and optical properties. The second part of this chapter deals with the characteristics of ice in nature produced by liquid water freezing, such as sea ice or the perennial ice present in ice caps and icebergs. These characteristics will affect the transportation of ice, determine the extent to which icebergs can be used for water supply and provide information for spatial interaction models, operational research and the optimisation of the distribution and scheduling of transporting icebergs.

2.1 Water Cycle

Earth biosphere water exists in different quantities, under different forms on lands, oceans and in the atmosphere and change place in cycles (Figure 2.1).

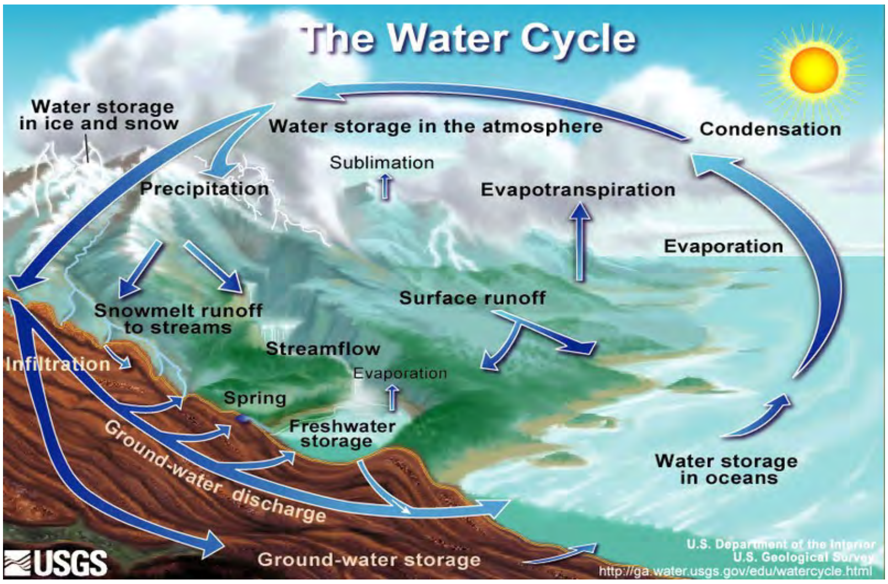


Figure 2.1 The Earth's Water Cycle (credit Evans, USGS[2], n.d. n.p.)

Water covers about 75% of the Earth's surface and takes different forms such as sea water and icebergs in oceans, glaciers, lakes, rivers and aquifers in the ground in the hydrosphere and water vapour in clouds in the atmosphere (Table 2.1). Freshwater is stored in lakes, rivers, ice caps, snow pack glaciers and icebergs (Table 2.2).

Table 2.1 Seawater and Freshwater in Hydrosphere (from USGS, 2010, n.d. n.p.)

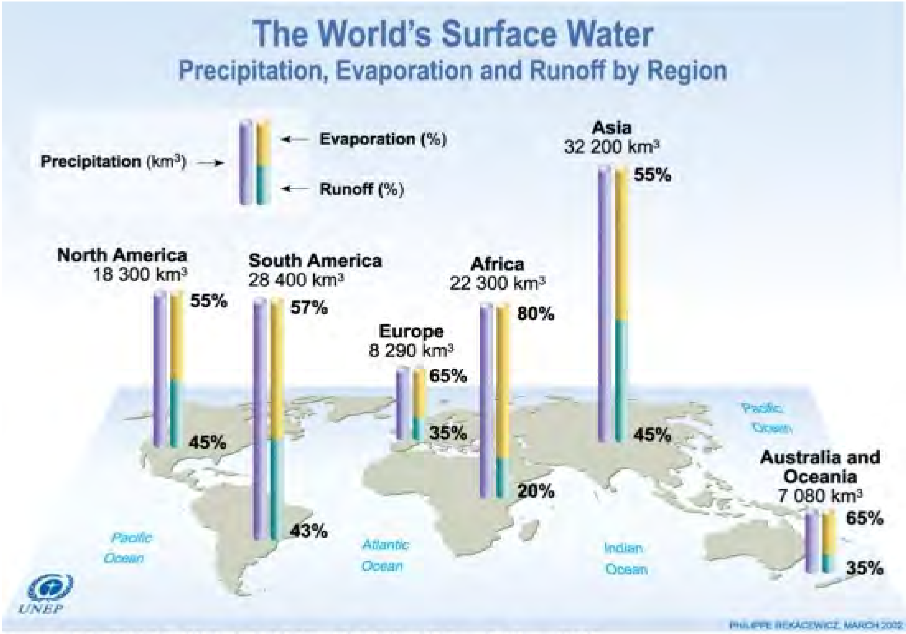
Water	**Percentage %**	**Volume Million km^3**
Hydrosphere	100	1360,000
Seawater	96.2	1,300,000
Freshwater	3.8	> 60,000

Table 2.2 Freshwater in Biosphere (from USGS, 2010, n.d. n.p.)

Freshwater	**Freshwater repartition**	**Components**	**%**	**Million km^3**
Iced freshwater	Oceans and continental	Icebergs, glaciers, ice caps, snow packs	70	45
Liquid freshwater			30	13
	Superficial continental	Rivers, lakes, clouds, part of atmospheric vapours	< 1	< 1
	Underground	Aquifer	29	> 12
	Atmosphere	Vapours	0.001	0.013

[2] https://ga.water.usgs.gov/edu/watercycle.html

The water cycle consists of three main transfer processes: evaporation, precipitation and runoff (Figure 2.2).



Source: Peter H. Gleick, *Water in Crisis*, New York Oxford University Press, 1993.

Figure 2.2 World's Surface Water: Precipitation, Evaporation and Runoff (credit Gleick, 1993 n.p.[3])

Precipitation is produced by the condensation of water vapour in the air falling back down to the earth and oceans as rain (Figure 2.3), snow, hail, fog and dew.

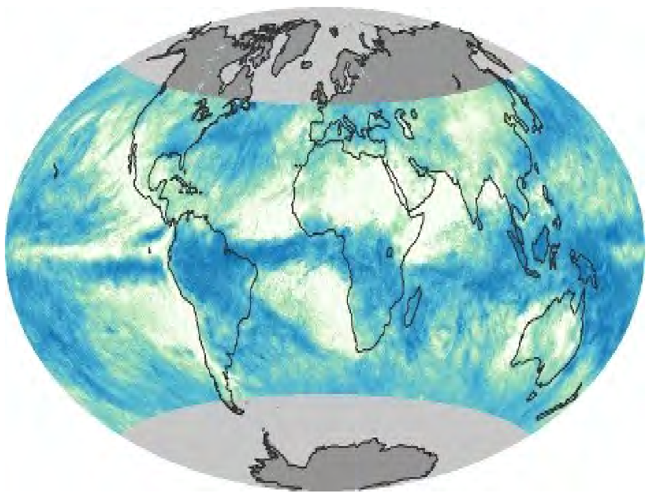


Figure 2.3 Total Rainfall. From 0 to 2 m (credit NASA, 2009 n.p.[4])

[3] http://maps.grida.no/go/graphic/world-s-surface-water-precipitation-evaporation-and-runoff

Freshwater runoff is produced by rain water, snow melt and other phenomenon over continents. Evaporation and transpiration contributes 71,000 km^3/year and precipitation contributes 104,000 km^3/year over land, against 390,000 km^3/year over oceans (Leeden *et al.*, 1990). Approximately 500,000 km^3 of water falls as precipitation each year, 398,000 km^3 of it over the ocean which indicates the globally-averaged annual precipitation is 1m, and the average annual precipitation over oceans is about 2 m (Chowdhury, 2005). The difference between the precipitation and evaporation figures correspond to river flows 25,000 km^3/year, underground flows 10,000 km^3/year, ice melt 3,000 km^3/year and atmospheric water and glacier production 3,000 km^3/year. The differences in the water cycle can be explained by a heterogeneous distribution of the water on the Earth's surface in quantity and quality. There is barely any evaporation in some regions, such as over ice sheets and hot and dry desert regions.

The world's annual renewable water resources (stored in clouds, rivers and ground water) are around 55,000 km^3. The renewability (residence, exit and new receptions) of water resources varies from eight to ten days in the atmosphere, one week in living organisms, two weeks in rivers and lakes, from two weeks to almost one year for underground waters or even several years in humid zones, and from several years to thousands of years for ice (Table 2.3).

Table 2.3 Freshwater Resources Regeneration and Renewability (credit, Gleick, 2009[5])

Freshwater resources	**Volume (km^3)**	**Regeneration time (days)**	**Time scale**	**Ratio daily production (km^3)**	**Resources**
Ice	33,000,000	365,500	10,000 years	9	Semi fossil resources
Underground water	11,000,000	36,550	1,000 years	30	Semi fossil resources
Superficial water	250,000	183	6 months	1,366	Most accessible reservoir
Atmosphere	45,000	15	2 weeks	3,000	Main circulation resource
Biosphere	13,000	10	10 days	1,300	Main consumption

Note: Human water consumption is in the order of less than 5,000 km^3

[4] http://visibleearth.nasa.gov/view_rec.php?id=1540
[5] www.worldwater.org/

2.2 Geophysical Environment

The cryosphere displayed in Figure 2.4 shows the zones of the Earth's surfaces covered with snow, ice sheets, glaciers, permafrost, sea ice, lake ice, and river ice (AAD[6]).

Figure 2.4 The Cryosphere (credit Ahlenius[7], 2007, NGA, 2000 n.p.)

Snow cover is a significant element in the water cycle and has a maximum extent of about 47 million km². Sea ice is formed by sea water freezing and covers both polar oceans. Satellite data reveals a large temporal variability in the coverage of sea ice in both Northern and Southern Hemispheres.

2.3 Characteristics of Ice

Ice is a mineral and is a crystalline solid substance which forms at temperatures below 0°C (frozen liquid or vapour water) (Eicken, 2003). Ice can also be defined as the solid form phase of water on Earth. A snowflake is a single ice crystal. Below 0°C, liquid water becomes solid (river ice, sea ice, hail, or refrigerated ice). Ice occurs in different forms on Earth. Glaciers contain perennial ice. Ice also occurs on land as permafrost. In the polar oceans, ice caps and icebergs are formed by both ice breaking off from glaciers or ice shelves and seawater freezing.

[6] www.aad.gov.au
[7] maps.grida.no/go/.../the-cryosphere-world-map

The physics of ice will be described from descriptions by Pounder (1965[8]), Fletcher (1970), Hobbs (1974), Glen (1975) and Maeno (1981). The CRREL, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, USA reports, and a book written by Petrenko and Whitworth (1999) are also worthy of mention.

2.4 Ice Phases

Figure 2.5 is a phase diagram of water and represents water transition from a liquid state to an ice state as a function of temperature and pressure.

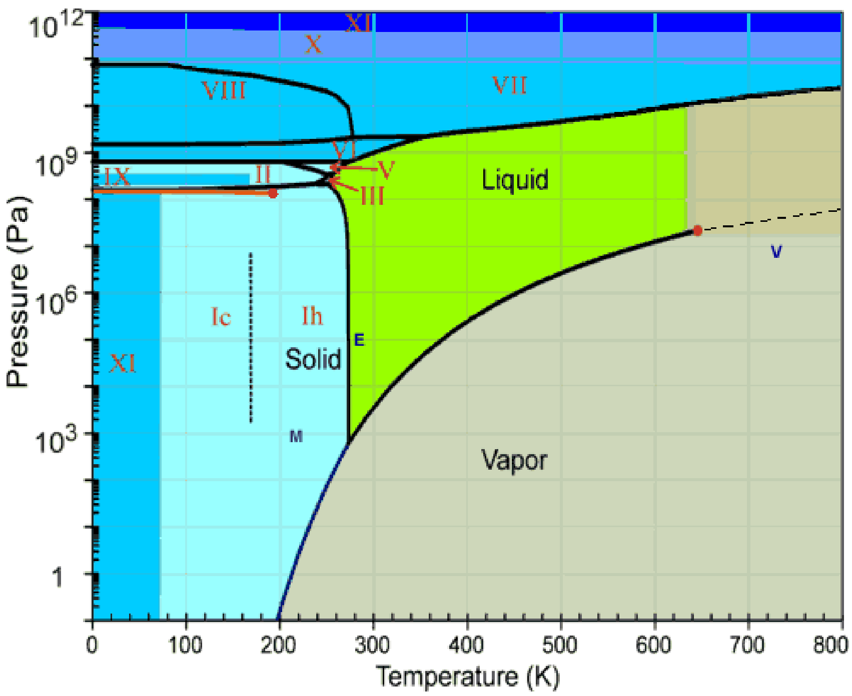


Figure 2.5 Phase Diagram of Water (credit Govindarajan, n.d.[9], King, 2009 p. 3). Types of ice in red

Several phases of ice can be defined. The ice in everyday life is known as ice I_h. The $_h$ indicates that the symmetry of the ice crystal is hexagonal in shape. Additional phases called ice II and ice III have been created under special laboratory conditions. Pounder (1965 p.10 cited by Touretzky 1998[10]) explained that:

[8] http://www-2.cs.cmu.edu/~dst/ATG/ice.html
[9] http://sgovindarajan.wikidot.com/notes:phase-transitions, http://www.colorado.edu/physics/phys4230/phys4230_sp02/images/phase.gif
[10] http://www-2.cs.cmu.edu/~dst/ATG/ice.html

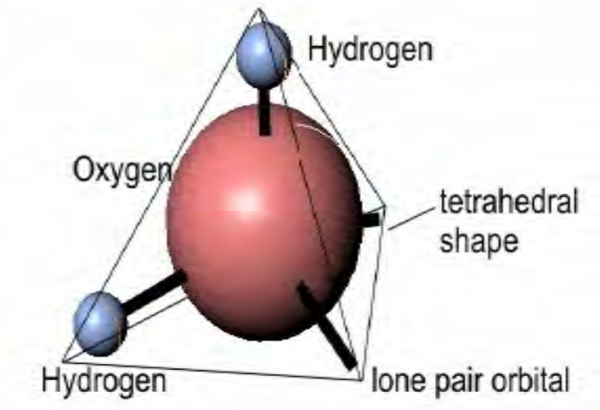
> Except at temperatures lower than those occurring naturally on the earth, none of these ices [Ice II to Ice IX] can exist at pressures of less than 2,000 atmospheres. Since the thickest ice sheet in the world is in Antarctica and is less than 4,000 m thick, corresponding to a maximum pressure at the base of the ice of about 350 atmospheres, it is clear that none of these artificial ices can normally exist on Earth.

In this thesis, the term ice stands for ice I_h.

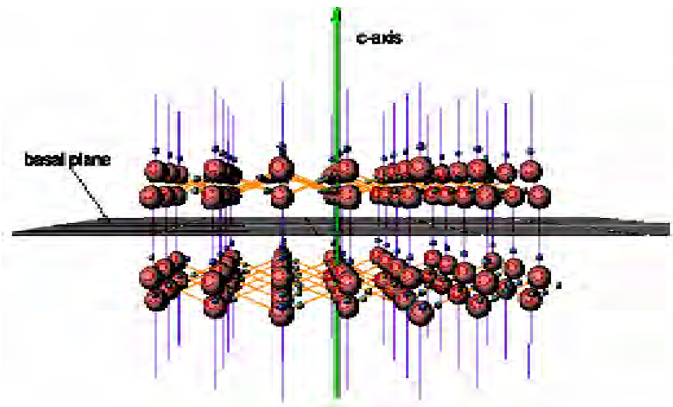
2.5 Ice I_h

An ice crystal is structured of oxygen atoms linked in hexagonal rings (Figure 2.6a, b and c).

a.



b.



c.

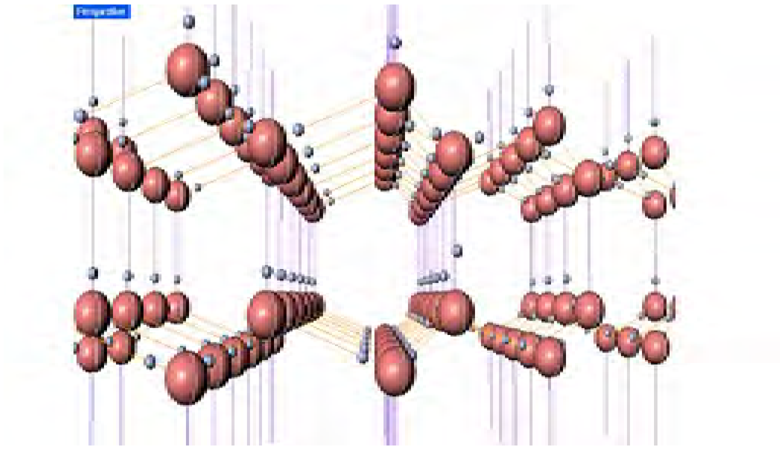


Figure 2.6 Ice Crystal Lattice (credit Daley, 2007 pp. 1-4[11])
Legend: a. water molecules, b. bonding within layers, c. ice crystal lattice

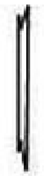
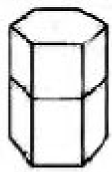
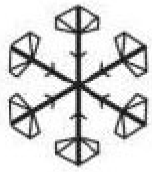
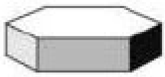
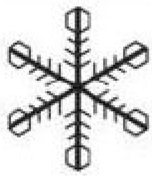
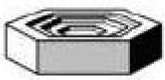
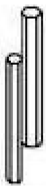
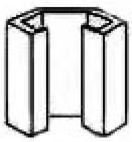
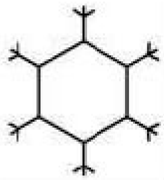
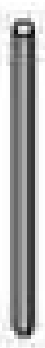
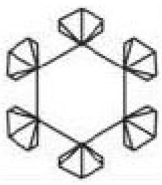
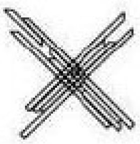
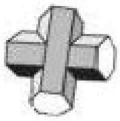
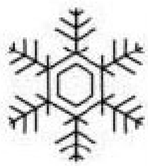
According to Smith and Schulson (1999 p. 21[12]), "[T]he oxygen atom of each molecule is strongly covalently bonded to two hydrogen atoms, while the molecules are weakly hydrogen bonded to each other". Two protons are located near each oxygen and only one proton lies on each O - O bond. The *c*-axis is parallel to the hexagonal rings of the crystal structure. The *c*-axis is the optical axis of the crystal structure[13]. Schulson (1999 p. 21) explains that "[T]he lattice parameters near the melting point are: a = 0.4523 nm; and c = 0.7367 nm. The ratio c/a = 1.629 which is very close to the ratio of melting point (the ideal ratio of 1.6330)".

All the O - O bonds have the same length. Therefore the anisotropy of thermal and elastical properties is small. The ice unit cell is relatively open, which explains why the density of ice is lower than water density. The symmetric growth forms of snow crystals make snowflakes. The diameter of such crystals ranges between one and two millimetres. It is often supposed that all natural snowflakes take this form. In reality, these structures are often broken, malformed or rimed with frozen droplets. In nature a great variety of habits are possible and these have been classified together with the irregular forms by Nakaya (1954) and Magono and Lee (1966). These habits range from long thin needles through columns to plates (Figure 2.7) and each form may be simple or dendritic (forming tree-like crystals). The

[11] http://engr.mun.ca/~cdaley/8674_docs.htm
[12] http://www.tms.org/pubs/journals/JOM/9902/Schulson-9902.html
[13] http://www.britannica.com/EBchecked/topic/87357/c-axis

simpler habits are related to the environment in which the crystal grew. Ice crystals can grow in two simple distinct ways:

- by the freezing of liquid water;
- by direct sublimation from the vapour phase.

	***N1a*** Elementary needle		***C1f*** Hollow column		***P2b*** Stellar crystal with sector-like ends
	***N1b*** Bundle of elementary needles		***C1g*** Solid thick plate		***P2c*** Dendritic crystal with plates at end
	***N1c*** Elementary sheath		***C1h*** Thick plate of skeleton form		***P2d*** Dendritic crystal with sector-like ends
	***N1d*** Bundle of elementary sheaths		***C1i*** Scroll		***P2e*** Plate with simple extensions
	***N1e*** Long solid column		***C2a*** Combination of bullets		***P2f*** Plate with sector-like extensions
	***N2a*** Combinatio n of needles		***C2b**** Combination of columns		***P2g*** Plate with dendritic extensions

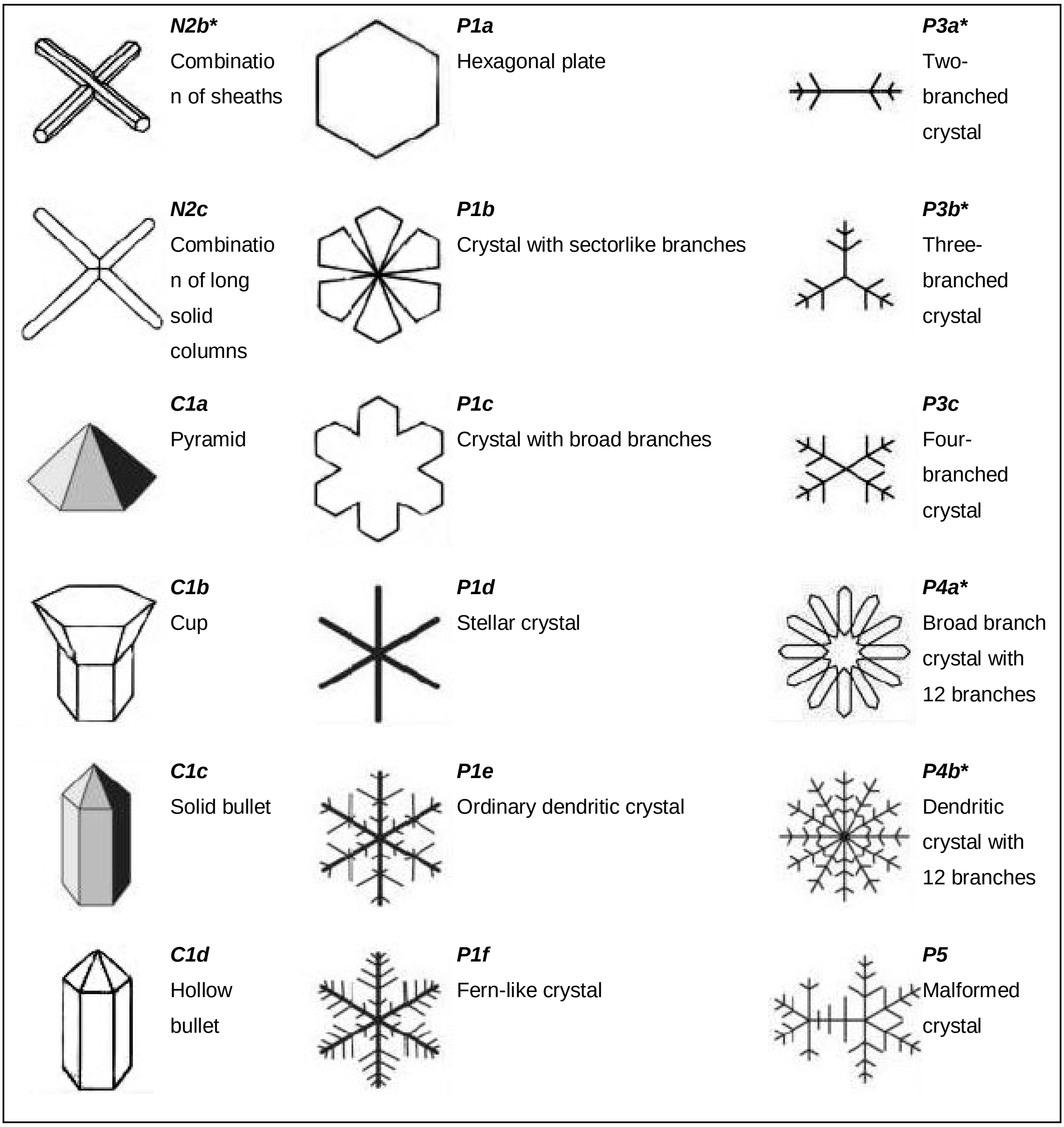


Figure 2.7 Classification of Snow Crystals (credit Magono and Lee[14],1966 n.p.)

In each case the mechanisms which determine the rate and habit of growth are the transport of water molecules to the point of growth and their accommodation into the growing

[14] http://emu.arsusda.gov/snowsite/Magono_and_Lee/Magono_and_Lee_Classification1.html see also www.dri.edu USDA, ARS, PSI, NASA http://www.its.caltech.edu/~atomic/snowcrystals/class/class.htm

interface, together with the transport of latent heat away from this interface (Fletcher, 1971[15]). The grain orientation is usually:

- with the c-axis perpendicular to the interface, crystals develop as thin circular disks;
- with the c-axis parallel to the interface, crystals develop as long needles.

The structure of a perfect ice crystal must satisfy the following three rules (Fletcher, 1970; Hobbs, 1974; Petrenko, 1993; Petrenko and Whitworth, 1999):

1. each lattice position is occupied by a water molecule tetrahedral bonded to its four neighbours;
2. water molecules are intact so that there are just two protons near each oxygen molecule;
3. there is just one proton on each bond.

Violation of these rules leads to a vacancy (for the first rule), an interstitial or an impurity atom (for the second rule) and defects perpendicular to the ice structure (for the third rule). In ice crystals occurring in nature many imperfections can occur, such as: variations in surface properties, impurities, dislocations, vacancies, orientation or planar defects and other various kinds of point defects. Sea ice has various inclusions; freshwater ice has no inclusions. Whilst most of the impurities in liquid water remain preferentially in the liquid phase when it begins to freeze, it is possible to include small amounts of some materials in true solid solution in an ice crystal. Two types of impurities (proton donors and proton acceptors) can change the balance of ion states and of orientation defects in the ice crystal. Proton donors can enter while the ice structure replacing a water molecule, while proton acceptors can be incorporated in the ice structure inducing defects. Impurities can be transferred by solid-state diffusion or they can stay on the ice lattice. In any crystal there will be a certain concentration of vacancies and interstitial molecules in thermal equilibrium. In ordinary ice at atmospheric pressure the energy required to form a vacancy is essentially the energy necessary to remove the molecule from the bulk of the crystal and place it in a general position on the surface (12 kcal/mole, or 0.5 eV). Vacancies and interstitials exist in thermal equilibrium in ice. Their concentrations are small even at the melting point and for this reason the density of ice crystal (917 kg/m^{-3}) measured by macroscopic means agrees

[15] http://newt.phys.unsw.edu.au/music/people/publications/Fletcher1971.pdf

closely with the value derived from X-ray determination of lattice constants (Fletcher, 1970; Petrenko, 1993[16]).

The growth of ice crystals from water vapour is a familiar phenomenon since a major part of the growth of snowflakes occurs in this way. Simple or complex habits can be observed. The simpler habits of ice crystals can be related to the environment in which the crystal grows. Mixed forms of ice crystals, such as columns tipped with plates, occur in crystals whose environment altered during the course of their growth. The diversity of ice crystal habits provides useful meteorological information about the chemical and physical conditions inside clouds, having an effect on ice crystals growth, such as the presence and type of contaminants and the temperature and the super-saturation of the vapours.

Figure 2.8a and Figure 2.8b show the regions of occurrence of different crystal habits, in relation to temperature and vapour super-saturation.

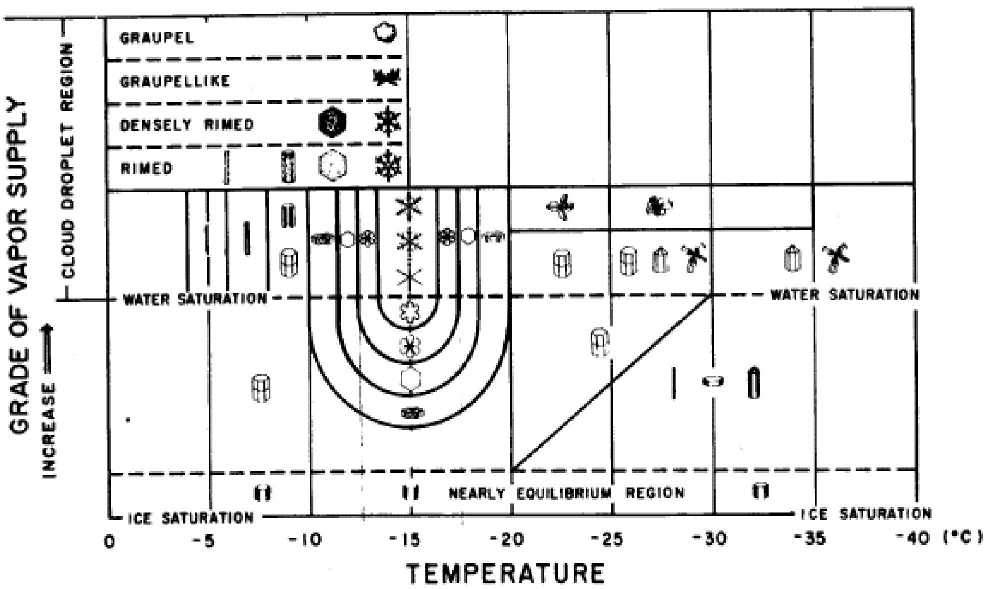


Fig. 2-26. Temperature and humidity conditions for the growth of natural snow crystals of various types. (From Magono and Lee, 1966; by courtesy of *J. Fac. Sci.*, Hokkaido University.)

Figure 2.8a The Regions of Occurrence of Different Growth Crystal Habits, in Relation to Temperature, Humidity Conditions and Vapour Super-saturation (credit Magono and Lee, 1966, from Fletcher, 1970 n.p.)

16 http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA270432

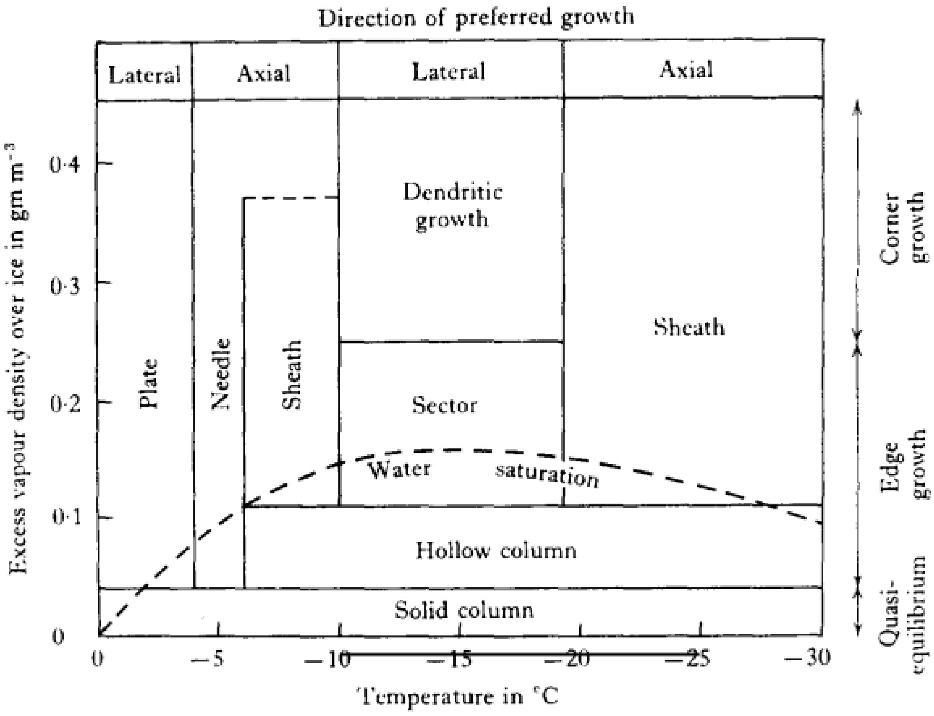


Figure 2.8b The Nakaya Diagram (credit Fletcher, 1973 p. 268[17])

The temperature dependence of crystal habits is specific. The vertical lines divide temperature regions in which the crystals' growth is alternately axial, leading to long needles oriented parallel to the c-axis, and lateral, yielding flat hexagonal plates. The transitions between the different growth regimes are very sharp. At high super-saturation the crystal forms become more and more complex and tend to lead to dendritic development - planar, scrolls, cups or hollow prisms - depending on the temperature range. Lawson *et al*. (2006) reported the collection of 900,000 ice crystals at the South Pole Station from the 1st of February to 8th of February 2001. Some of these ice crystals are shown in Figure 2.9.

[17] https://phys.unsw.edu.au/music/people/publications/Fletcher1973.pdf

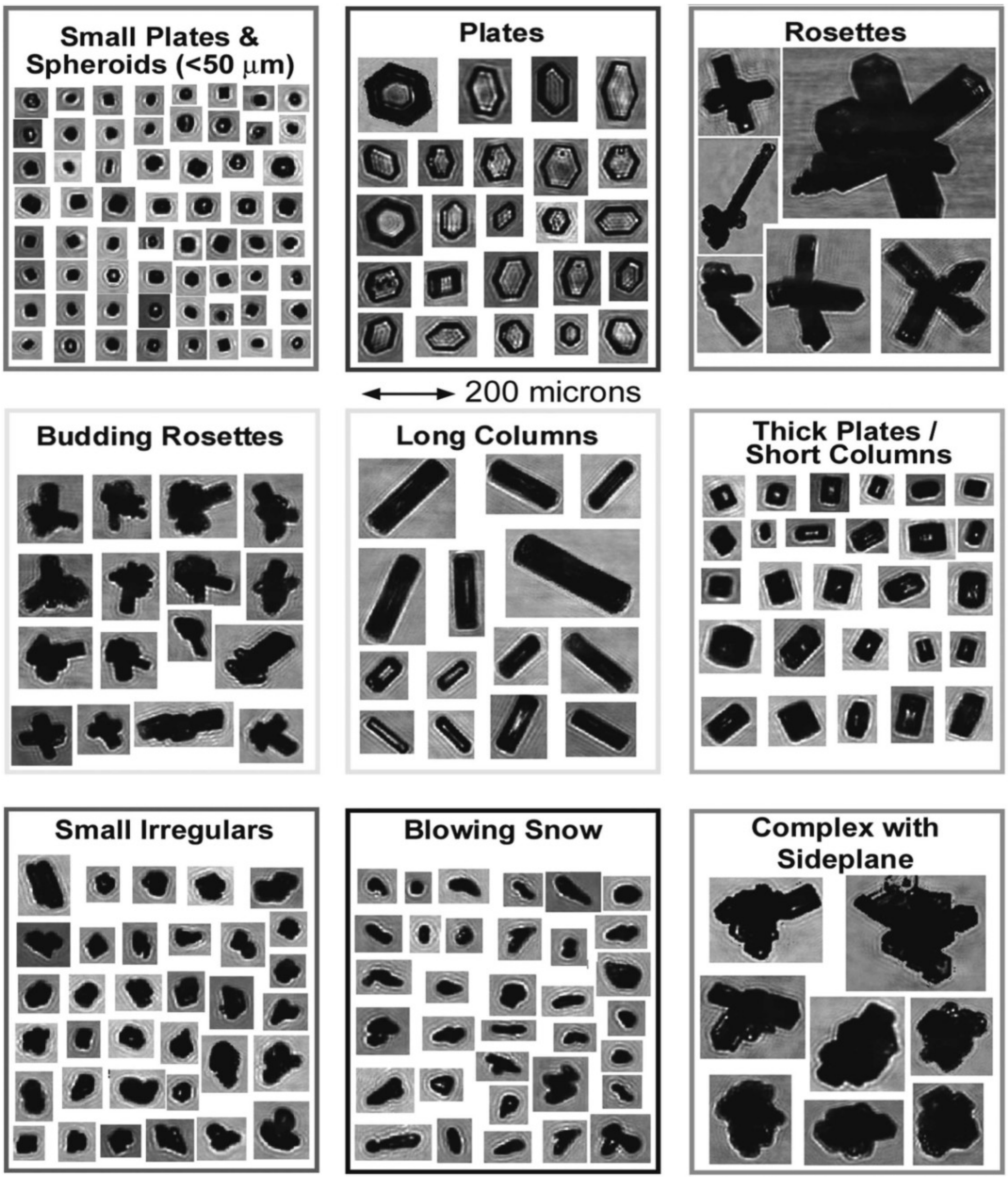


Figure 2.9 Ice Crystals (credit Lawson *et al*., 2006 p. 1512[18])

According to Lawson *et al.* (2006 p. 1505[19]) "[T]he size, shape, concentration and light-scattering properties (i.e. phase function) of ice crystals have a major impact on the Earth's radiation budget". Modern methods of micro structural analysis are providing us with unprecedented detail of 3D microstructure using modern tools for modelling of ice behaviour (Petrenko and Witworth, 1999). According to Eicken *et al.* (2005 p. 5): "[B]y averaging over the individual microscopic component phases one arrives at a macroscopic representation of

[18] http://journals.ametsoc.org/doi/pdf/10.1175/JAM2421.1
[19] http://journals.ametsoc.org/doi/pdf/10.1175/JAM2421.1

the material where the specific properties of the microscopic component phases are subsumed in a single bulk parameter". Micro structural model are used in these areas of study. At the same time at the macro scale, models only barely incorporate more complex or sophisticated representations of ice characteristics, commonly referred to as parameterisations of processes and properties on smaller scales (Steele and Flato, 2000). Moreover, according to Eicken *et al.* (2003 p. 2[20]):

> Ice microstructure requires that conceptual and mathematical models and representations of ice properties consider in detail the volume fraction, size, shape and spatial arrangement of brine gas and particulate inclusions. For scalar quantities, such as ice density, only the volume fraction of inclusions is of concern (Cox and Weeks, 1988), whereas tensor properties such as the [mechanical characteristics], thermal conductivity or permeability require a more sophisticated approach.

According to Eicken *et al.* (2003 p. 20):

> The packing density of water molecules in ice and hence its material density is lower than in the liquid [state]. In the liquid state, water molecules are arranged into clusters with impurities such as sea salt ions surrounded by hydrates shells owing to the strong polarity of the water molecule. Accommodation of sea salt ions in the voids of the ice crystal lattice is greatly restricted, however. The constraints in size and electric charge imposed on ions or molecules substituting water molecules or individual atoms in the lattice or occupying voids within the crystal lattice are such that only very few ions or molecules actually qualify. Among them are fluorine and ammonium ions and some gases. The major ions present in sea water (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_2^{-4}, CO_2^{-3}), however, cannot be incorporated into the ice crystal lattice and are rejected by the advancing ice-water interface during crystal growth. This circumstance has very important consequences for the microstructure and properties of sea ice, as part of the salt is retained in liquid inclusions in the solid ice matrix, with a larger fraction rejected into the underlying water column.

The salt migration happens in a different way in freshwater as salt water ice. The phase diagram of sea ice is given in Figure 2.10.

[20] www.gi.alaska.edu/ftp/eicken/G695/Module1/Papers/Chapter2.pdf

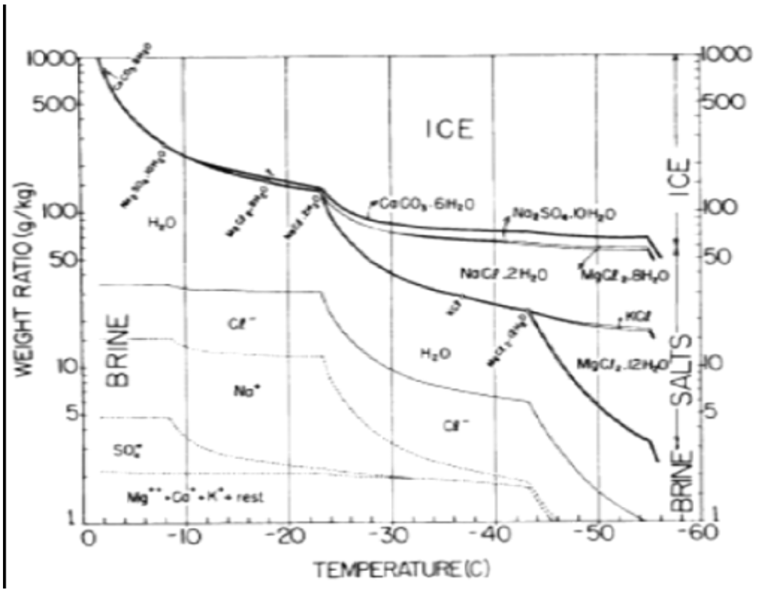


Figure 2.10 Phase Diagram of Sea Ice (credit Assur, 1960 n.p.[21] from Eicken 2003 p. 21, 2009, p 29).

Micro structural evolution and chemical composition of ice are interacting at the few centimetres thick bottom layer which is characteristic of the different types of ice (Eicken, 2003).

Single crystals can be grown in a laboratory environment, but it is difficult to achieve crystals of a large size. In Antarctica single crystals which can be several kg in weight of exceptional purity and mechanical perfection are found. Presumably these crystals have been produced over centuries by a process known as strain annealing. The properties of this type of ice will be described now.

2.6 Properties of the Ice Crystal Lattice

In this section the thermal, mechanical, electrical and optical properties of pure ice crystals will be briefly discussed. Table 2.4 summarizes some properties of ice crystals at 0°C, described previously.

[21] www.gi.alaska.edu/ftp/eicken/G695/Module1/Papers/Chapter2.pdf, see also http://glaciology.caltech.edu/ice.fig2.html

Table 2.4 Physical Properties of Ice I_h at 0°C (credit Engelhardt[22], 1992 n.p.)

Physical Characteristics of Ice	Values
Density	0.917 Mg m^{-3}
H-bond length	276.5 pm
Adiabatic compressibility	0.119 GPa^{-1}
Isothermal compressibility	0.33 GPa^{-1}
Melting point	273.15 K
Specific heat	2.01 $kJ/kg^{-1}/K^{-1}$
Heat of melting	334 kJ/kg^{-1}
Thermal conductivity	2.2 $W/m^{-1}K^{-1}$
Linear expansion coefficient	$55{\cdot}1O^{-6}$ K^{-1}
Cubical expansion coefficient	$166{\cdot}1O^{-6}$ K^{-1}
Vapour pressure	610.7 Pa
Static dielectric constant	96.5
High-frequency dielectric constant	3.2
Dielectric relaxation time	20 µs
Activation energy for dielectric relaxation	55 kJ/mol^{-1}
Refractive index	1.31
Electric dc conductivity of ice single crystals at -10°C Electric dc conductivity of polycrystalline glacier ice	$2{\cdot}10^{-8}$ S/m^{-1} 10^{-5} - 10^{-6} S/m^{-1}
Proton mobility	$0.8{\cdot}10^{-4}$ $m^2/V^{-1}/s^{-1}$
Ultrasonic velocity Longitudinal waves and Transverse wave	1928 m/s and 1951 m/s
Velocity of radio waves	170 $m\mu s^{-1}$

These values could be used for the development of new techniques for icebergs detection (Veitch and Daley, 2001):

- acoustical properties (e.g. ultrasonic velocity) can be used for detecting with ultrasonic techniques the shapes of icebergs and their mechanical characterisation;
- dielectrical properties (e.g. dielectric relaxation time, static dielectric constant, high-frequency dielectric constants, activation energy for dielectric relaxation) can be used for icebergs detection and the evolution of iceberg shapes during their melting;
- mechanical properties (e.g. compressibility, density) can be used to select icebergs, icebergs given their erosion and melting evolution and to test iceberg stability;

[22] http://glaciology.caltech.edu/ice.table2.html

- thermal properties (e.g. conductivity, linear expansion coefficient, cubic expansion coefficient melting point, vapour pressure, specific heat, proton mobility, H-bond length) can be used to record icebergs evolution in terms of thermodynamic decay and for the development of non contact techniques for icebergs detection;
- optical properties (e.g. Refractive index) can be used for detection and deterioration modelling of icebergs.

Such studies could contribute to the development of a model of iceberg transportation regarding the deterioration and the stability of transported icebergs.

2.6.1 Thermal Properties

The thermal properties of ice crystals derive essentially from the thermal motion of water molecules within the crystal structure (Andersson and Suga, 1994). The thermal properties related to lattice dynamics are heat capacity, conductivity and expansion. At low temperature the thermal expansion coefficient is negative. Its value increases with increasing temperature between 50 and 250°K. At 0°C, the linear expansion coefficient has a value of 55.10^{-6} K^{-1}. The thermal conductivity of ice I_h at 0°C is 2.2 $W.m^{-1}/K^{-1}$ (Fukusako, 1990; Kim and Ulrich, 2002). Also note that thermal conductivity is dependent on temperature and pressure. The anisotropy of ice measured by the thermal conductivity of single crystals near 270°K, is around 5% (Slack, 1980). The thermal conductivity of polycrystalline and single crystal ice yield similar thermal conductivity results, as long as the crystallites are large enough to avoid the effect of grain boundary scattering. Grain size of $< 10^{-3}$ cm would be needed to affect the thermal conductivity above 80°K.

2.6.2 Mechanical Properties

The mechanical properties of a single ice crystal are studied in an elastic and plastic domain. In an elastic domain the stress applied to the crystal is relatively small and is applied over a short time[23]. The elastic behaviour is characterised by the elastic constants (Dempsey, 2000). The relaxation parameters are important because of periodically varying stresses. If the stresses are large, the specimen may suffer important permanent deformation and then the mechanical behaviour is related to plastic deformation, creep and fracture (Xiao and Jordaan, 1996; Barrette and Jordaan, 2002). The phenomena related to permanent

[23] http://www.tms.org/pubs/journals/JOM/9902/Schulson-9902.html

deformation and crystal lattice fracture are very important for understanding glacial flow and iceberg formation. The mechanical behaviour of solids in an elastic regime is governed by Hook's law, which suggests there is proportionality between stress tensor [**σ**] and strain tensor [**ε**] through the compliance tensor [**S**]:

[**ε**] = [**S**] [**σ**] or [**σ**] = [**C**] [**ε**]

Where [**C**] is the stiffness tensor.

Ice crystals are anisotropic and have a hexagonal symmetry. In the case of hexagonal symmetry, the stiffness tensor [**C**] has five components: C_{11}, C_{33}, C_{44}, C_{12}, C_{13} (Nye, 1957). The components C_{11} and C_{33} can be determined with ultrasonic methods, measuring the velocity of propagation of longitudinal waves along the crystallographic axes *a,* and *c*. The shear component C_{44} is determined using the velocity of shear waves propagating in the plane *ac*. The components C_{12} and C_{13} include Poisson's effect and represent the coupling between the constants measured with longitudinal and shear waves. The mechanical behaviour is dependent of temperature and pressure. Table 2.5 gives the values of the stiffness components as reported by Fletcher (1970).

Table 2.5 The Components of Stiffness Tensor [**C**] of Ice [10^8 N/m²] at -16°C (credit Fletcher, 1970)

C_{11}	C_{33}	C_{44}	C_{12}	C_{13}
13.85	7.07	3.19	7.07	5.81

Note: 1 N/m² = 1 Pa; 1 MPa = 10^6 N/m² 13.85 [10^8 N/m²] = 1385 MPa

The two Young's module and Poisson's coefficients can be deduced by inverting the stiffness matrix as [**S**] = [**C**]$^{-1}$ following the procedure largely described in reference books for materials characterisation. For a less complex mechanical characterisation of the polycrystalline ice, Fletcher (1970) suggested using the isotropic symmetry C_{11} = C_{33}. In this case only three elastic constants are needed: Young's modulus (E), shear modulus (G) and Poisson's coefficient (γ). These constants are related as G = E/[2(1+γ)]. The values of these constants at -5°C and normal atmospheric pressure are:

E = (8.8 to 9.9) [10^8 N/m²]; G = 3.4 to 3.8 [10^8 N/m²], Poisson's ratio = 0.31 to 0.36

Mechanical relaxation is associated with the internal friction of the material. This leads to the damping of the free mechanical vibration and is expressed by the logarithmic decrement (noted *δ*) for different vibration modes in ice specimens. Some experimental values for specimens oriented parallel or perpendicular to the axis *c* and excited with longitudinal waves are: $\delta_{//} = 0.35 .10^{-2}$ and respectively $\delta \perp = 2.5 .10^{-2}$ (Fletcher, 1970).

2.6.3 Electrical Properties

The electromechanical effects of ice may have important practical applications in ice engineering. The electrical properties of ice have been studied extensively for more than 50 years and substantial progress has been achieved in the last decade. The mechanical and electrical properties of ice are very strongly connected (Petrenko, 1996[24]) and can be observed through phenomena such as:

- the generation of an electromagnetic field by elastic stress, plastic strain, fracture, and friction;
- the modification of the mechanical properties, such as elasticity, plasticity and friction, by the application of an electrical field;
- the modification of the electrical conductivity and dielectric permittivity by the strain.

2.6.4 Optical Properties

The optical properties of ice were studied by Perovich (1998; 2002[25]). Pedersen (2007, p. 6[26]) noted that:

> The radiative transfer in sea ice is determined by the absorption and scattering coefficients, brine and impurities. Air bubbles scatter more strongly than brine pockets because of larger decreases in refraction index compared to ice. An increasing number of inclusions in sea ice will increase the amount of scattering (Perovich, 2002). Snow has a large number of small grains and ice/air interfaces, which makes it a highly scattering medium, however, particles, like dust or soot in the snow, absorbs light, and thereby reduce the scattering.

[24] http://permanent.access.gpo.gov/websites/armymil/www.crrel.usace.army.mil/techpub/CRREL_Reports/reports/sr96_02.pdf
[25] http://www.crrel.usace.army.mil/sid/perovich/DKPpdf/97JC01615.pdf,
[26] http://www.ub.uit.no/munin/bitstream/10037/1909/5/thesis.pdf

The albedo scattered back from ice depends on the amount absorbed within the ice column. According to Perovich (1998) cited by Eicken (2003 p. 49): “the fraction that ultimately penetrates into the ocean depends on the relative contribution of absorption and scattering or reflection along the path of individual photons”. By definition the spectral albedo of the sea is a measure of sun reflected light and is about 0.9 on the scale 0 (dark object) to 1 (brilliant object). Gas, salt inclusions, and bio components in ice refractive indices affect the reflected incident irradiance. In Antarctica the average albedo value is 0.8. The growth of sea in winter ice determines the increase of the albedo values. In summer, the contrary effect occurs.

2.7 Ice in Nature

According to Ngheim *et al.* (1994[27] p. 6):

> Natural ice is a polycrystalline medium composed of many single crystals with different orientations. Beneath a thin transition layer, sea ice becomes columnar in structure with the C-axis parallel to within a few degrees of the horizontal plane (Weeks and Ackley, 1982) … Because the c-axes are parallel to the [horizontal] plane, the ice platelets are vertical. Consequently ellipsoidal brine inclusions, sandwiched between the platelets, are preferentially oriented in the vertical direction. Unless c-axes are aligned by an underlying sea current (Weeks and Gow, 1978).

The ice microstructure is polycrystalline and can be granular, columnar or mixed (Cole, 2000). The formation and growth of ice is related to the growth condition, the temperature (thermal gradient), salinity of the environment (brine pockets expulsed by pressure), flushing of melt water (by surface or gravity drainage), and the weather during which ice growth occurs. Common examples of ice in nature include sea ice, snow, glaciers and polar ice.

2.8 Glaciers and Polar Ice

According to Haykin *et al.* (p. 1994 p. 43), “[G]laciers form where precipitation in the form of snow exceeds its loss due to evaporation and or melting”. Newly fallen snow has a low density (0.06 to 0.08 g/cm^3) because of the air trapped between hexagonal snow crystals. The length of time for snow to be converted to ice largely depends on temperature. In temperate glaciers, where the ice is at the pressure melting point, the delicate snow crystals

[27] trs-new.jpl.nasa.gov, http://ieeexplore.ieee.org/iel2/3183/9015/00399177.pdf

melt quickly converting the snowflakes to spherical particles that settle and increase the density of the snow. The density can increase to 0.2 g/cm^3 in a few days (Thomas and Dieckmann, 2003). At this higher density, snow is granular. However, in sub polar and polar glaciers, this melting and compression process take years. Ice crystals grow larger by joining together and thus eliminate the air space between them. The firn or neve (ice at a stage between snow and glacial ice) occurs when the snow reaches a density between 0.4 and 0.55 g/cm^3. As the density increases further, mostly by re-crystallisation, the density can approach 0.85 g/cm^3. For Greenland glaciers it may take 150 to 200 years from the original snowfall event for ice to form (Thomas and Dieckmann, 2003). According to Haykin *et al.* (p. 1994 p. 44[28]) "because of this compression, glacial ice is impermeable to air and water. The visual whiteness of glacial ice is caused by the tiny air bubbles distributed throughout the ice" (Figure 2.11).

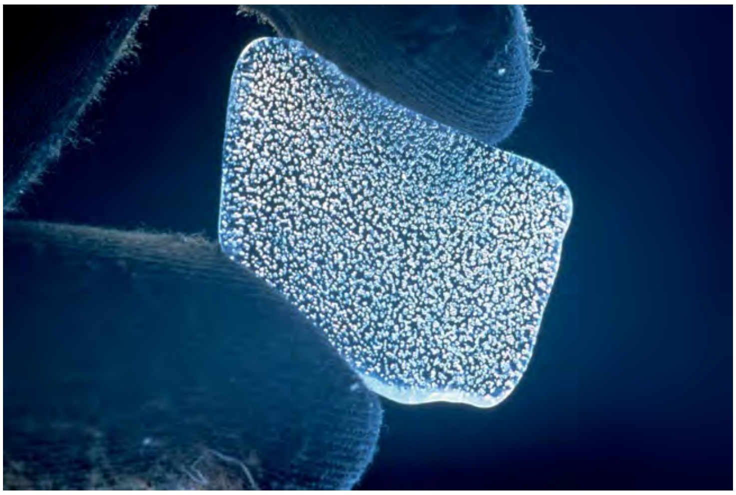


Figure 2.11 Antarctic Ice Revealing Bubbles of Air Inside (credit CSIRO Fraser, 2009 n.p.[29])

These bubbles give glacial ice a 4 to 9% volume of air. Scholander and Nutt (1960) reported that for Greenland icebergs the bubbles were elongated, with diameters of 0.02 to 0.18 mm. Gow *et al*. (1982) conducted a detailed analysis of bubble content in Antarctic glaciers and reported spherical bubbles that ranged in size from 0.49 to 0.33 mm, bubble size decreasing with glacial ice depth. Typical values for bubbles sizes in glacial ice are in the order of 0.1 to 0.5 mm (Gow *et al*., 1982). The occasional piece of bluish glacial ice indicates ice which is free of bubbles. Ice of comparable size and growth condition has a different optical

[28] http://books.google.com.au/books?id=1L8p6chyaYYC&printsec=frontcover&dq=Remote+sensing+of+sea+ice+and+icebergs+By+Simon+S.+Haykin&hl=en&ei=908ITbblEMmwcbXc-JoO&sa=X&oi=book_result&ct=result&resnum=1&ved=0CCsQ6AEwAA#v=onepage&q&f=false

[29] http://www.csiro.au/science/IcePhotoGallery.html

transparency. For example the appearance of lake ice is much darker then glacial ice, owing to its high transparency.

According to Thomas and Dieckmann (2003 p. 23[30]): "[T]he fact that the albedo of sea ice is typically higher than that of open water by a factor of up to ten gives rise to so-called ice albedo feedback processes. According to Eicken (2003 p. 4[31]) these processes involve:

> A perturbation in the surface energy balance resulting in a decrease in ice extent due to warming may propagate and amplify since the reduction in ice extent in turn increases the amount of solar energy absorbed by the system (Curry *et al*., 1995). For low-albedo lake ice, this effect is less pronounced. Under natural conditions, this contrast is affected by snow deposition in winter which increases albedo, at least prior to the onset of ice surface melt, and by the drainage of meltwater from lake ice, potentially bringing up albedo later in the melt season.

The final density of glacial ice can exceed 0.9 g/cm^3. Ice density is correlated with ice strength, the composition of the superficial layers (air bubbles can represent almost 50% of the volume of superficial layers), and the calving pressures which reduce the air proportion (less than 10% for iceberg). The general density of an iceberg is around 0.886 and can increase to 0.917 g/cm^3 if the ice is very compressed. As water has an average density of 1.028 g/cm^3, 87% of an iceberg's mass is under the sea (85% for tabular; 74% for pyramidal (Figure 2.12); 50% for dry dock icebergs).

Figure 2.12 Iceberg Ilulissat Rode Bay (credit ice blog[32] 2008 n.p.)

[30] http://books.google.com.au/books?id=F1MB5QIYJMsC&printsec=frontcover#v=onepage&q&f=false
[31] www.gi.alaska.edu/ftp/eicken/G695/Module1/Papers/Chapter2.pdf

The density of ice is around 900 kg/m^3 the density of seawater is around 1,025 kg/m^3. This explains why icebergs float. The ratio of these densities explains why 7/8th of a tabular iceberg's mass is below the water level.

These properties of ice are summarised in Table 2.6.

Table 2.6 Several Physical Constants of Ice (from Daley, 2007 and Lefrancois *et al.*, 2008)

Constants	Units	Fresh water ice (at 0°C)	First year sea ice (35‰ water, ice at -5°C)	Sea water	Air
Density	Kg/m^3	917	900	1,028	1,230
Melting point	°C	0	-1.8 (variable with water salinity)	-	-
Specific heat (heat capacity)	kJ/kg/°C	2.01	8	4 1	-
Latent heat of fusion or melt	kJ/kg	334	280	-	-
Thermal conductivity	W/m/°C	2.2	2.1	0.58	0.024
Linear expansion coefficient	1/°C	55.10-6	-	-	-
Vapour pressure	Pa	610	-	-	-
Refractive index	-	1.31	-	-	-
Dynamic viscosity	Ns/m^2	-	-	0.014	1.7 10-5
Absorptivity	-	0.95	-	-	-

2.9 Conclusion

The objective of this chapter was to describe the physical properties of ice in order to provide a broad context for the understanding of polar ice properties. Most of the properties listed above are critically dependent upon the structure of water molecules, which determine the possible crystal structures for ice and the way in which ice crystals can deform and rearrange. Polar ice is quasi chemically pure and much appropriated for freshwater supply. Polar ice is an exceptional resource of pure, renewable fresh water. The physical behaviour of ice studied in this chapter is essential to understand the natural perennial renewal and regular phenomenon of polar ice formation. This approach involves the study of physical properties of ice such as ice phases, ice crystal growing conditions, ice density, thermal, mechanical, acoustical, dielectrical and optical properties of ice. An iceberg transportation

[32] blogs.dw-world.de/ice-blog/images/news/8037.4.jpg

system is based on the melting, resisting, breaking, floating, and optical properties of icebergs as glacial and sea polar ice contributes to the formation of icebergs. The construction and maintenance of any iceberg transportation operations and infrastructures are reliant on the properties of the ice crystal lattice.

The acoustical properties could be used for the detection of icebergs with for example ultrasonic techniques of detection of the shape of icebergs. Dielectrical properties are employed for the development of remote sensing techniques for icebergs detection. The mechanical properties of ice such as density, the coefficient of linear expansion, dynamic viscosity, and vapour pressure are essential for iceberg selection, iceberg melting and evolution during transportation, iceberg erosion induced by ocean waves, solar radiation, and winds. Thermal properties such as melting point, specific heat, heat capacity, latent heat of fusion or melt, and thermal conductivity are connected to icebergs evolution in terms of thermodynamic decay and fragmentation and development of non contact techniques for icebergs detection. Optical properties such as the ice refractive index and the absorptivity of ice are related to detection and deterioration modelling of icebergs. This chapter has highlighted some of the critical properties of ice that are important factors in devising a system for the transportation of icebergs. The study of polar ice, as described above, is essential to understand technical issues of iceberg properties that may be required in any iceberg harvesting and transportation systems. Therefore iceberg ice appears to be the most suitable ice for an iced freshwater supply system. The upcoming chapter will study the significance and relevance of the physical properties of icebergs for iceberg harvesting and transportation systems.

Chapter 3 Properties of Icebergs

Figure 3.0 Iceberg Off Davis Station, Antarctica (credit CSIRO Blight[1], 2009 n.p.)

Icebergs icebergs religion-less cathedrals of the eternal winter …
Icebergs icebergs majestic Buddhas frozen on unseen seas …
Gleaming lighthouses of death lost howls, lasting for centuries …
Icebergs needless lonesome icebergs …
Icebergs icebergs cousins of islands, cousins of springs
How profoundly I see you, how familiar you are to me.
(Translated from Michaux 1934 p. 89)

[1]http://www.csiro.au/science/IcePhotoGallery.html

Chapter 3 Properties of Icebergs

The objective of this chapter is to describe the physical characteristics of icebergs. These characteristics impact the selection and operations research of iceberg transportation. From these studies, practical data for spatial interaction models, operational research, and the optimisation of the distribution and scheduling of the transportation of iceberg resources can be extracted. I will discuss the geography and physical properties of icebergs, the locations, the natural routes of icebergs and the melting and life expectancy of icebergs.

3.1 Geography of Freshwater Icebergs

Icebergs are located in the Polar Regions, the Arctic in Northern Hemisphere and Antarctica, in the Southern Hemisphere. The Arctic is a perennial ice covered ocean surrounded by frozen ground, and is comprising parts of Canada, US, Russia, Norway, Sweden, Greenland and Iceland. The boundary of the Arctic is the Arctic Circle, 66°33 N (Figure 3.1).

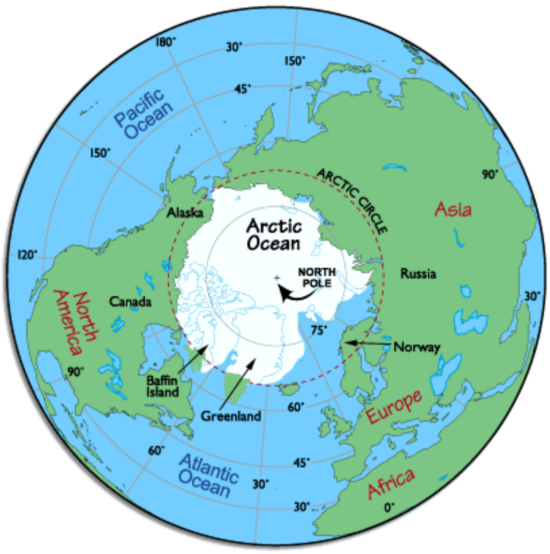


Figure 3.1 Arctic Ocean (credit World Atlas[2] n.d. n.p.)

Icebergs are floating in the Arctic Ocean (Darchen, 1977). These floating masses of freshwater ice have broken from ice sheets. The majority of icebergs in the North Atlantic originate from glaciers in Greenland. Others are from the Eastern Canadian Arctic islands, as far as 48° N (St John's) as reported by Canadian Ice Service and International Ice Patrol (2007). Antarctica is an ice-covered continent (Figure 3.2).

[2]http://www.worldatlas.com/webimage/countrys/polar/northpole.htm

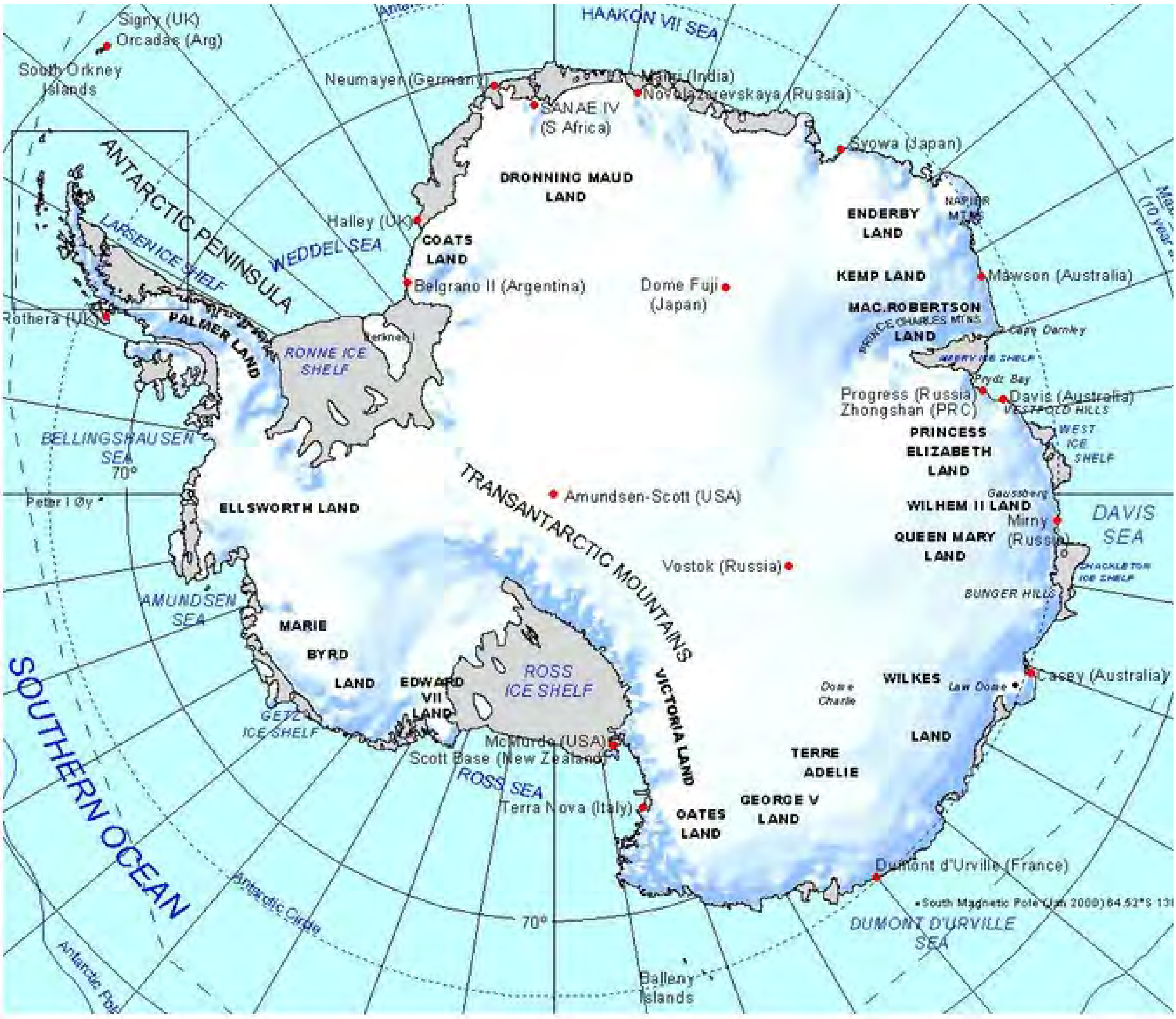


Figure 3.2 Antarctica (credit Australian Antarctic Data Centre[3] n.d. n.p.)

Ninety three percent of the world's mass of icebergs are located in the Antarctic seas (Stockinger from Encyclopaedia Britannica Volume 9, p. 154[4]). Antarctic coastlines are hidden beneath the ice flowing over the continental margins. In Antarctica, icebergs are generated by the mass of glaciers slipping under their own weight from the interior of the continent to the coast, becoming ice shelves and breaking off by ocean tidal oscillations and waves erosion. In the following pages icebergs classification is described.

[3] http://www.wunderground.com/climate/Antarctica.asp
[4] http://bioeng.berkeley.edu/budinger/icebergs.html

3.1.1 Iceberg Definition and Production

Kelley (1978 p. 20) defines icebergs as "large masses of floating or stranded ice which occur within both polar regions". Icebergs of many varied shapes originate from glaciers and are composed from freshwater. Fallen surface snow compacts on top of an ice sheet and becomes ice as the snow continues to accumulate. According to Young (AAD, 2001 p. 24[5]):

> The ice gradually flows outwards till it crosses the grounding line, the boundary between the grounded ice and floating ice. Along large sections of the grounding line, this ice flows into floating ice shelves. Ice is lost from the ice sheet by calving of icebergs from the outer perimeter and by melting from the basal surface of ice shelves and glaciers.

Icebergs break away from the seaward or glacial polar ice sheet. In situations where the basal shear stress of a glacier is inferior to the shear stress resulting from the glacier's weight, a glacier is said to move by sliding. The basal shear stress depends on the temperature of the glacial bed, its roughness and sediment strength (Clark *et al*., 1999). The creep of an ice sheet is a function of the thickness and the weight of the ice sheet, the temperature and the specific physical and mechanical properties of the ground on which it is sited. Glaciers may also move by basal sliding (Bennett, 2003). Their base is lubricated by melting water which can be provided by geothermal heat, friction or pressure inducing melting. According to Goodison *et al.* (2000[6] p. 270):

> [t]he mass balance of land-based glaciers and ice sheets is determined by the accumulation of snow mostly in winter and warm-season ablation due primarily to net radiation and turbulent heat fluxes, to melting ice and snow from warm-air advection (Munro, 1990; Paterson, 1993; Van den Broeke, 1996).

Glaciers melt when the sum of different radiation sources, including solar and long-wave incoming radiation, and heat flux is greater than the sum of heat of melt and long-wave outgoing radiation (Ohamura, 2007). The dynamics of icebergs generation from glaciers and continental shelves is schematised in Figure 3.3.

[5] http://www.antarctica.gov.au/__data/assets/pdf_file/0014/21182/p24_25_science.pdf
[6] http://eospso.gsfc.nasa.gov/science_plan/Ch6.pdf

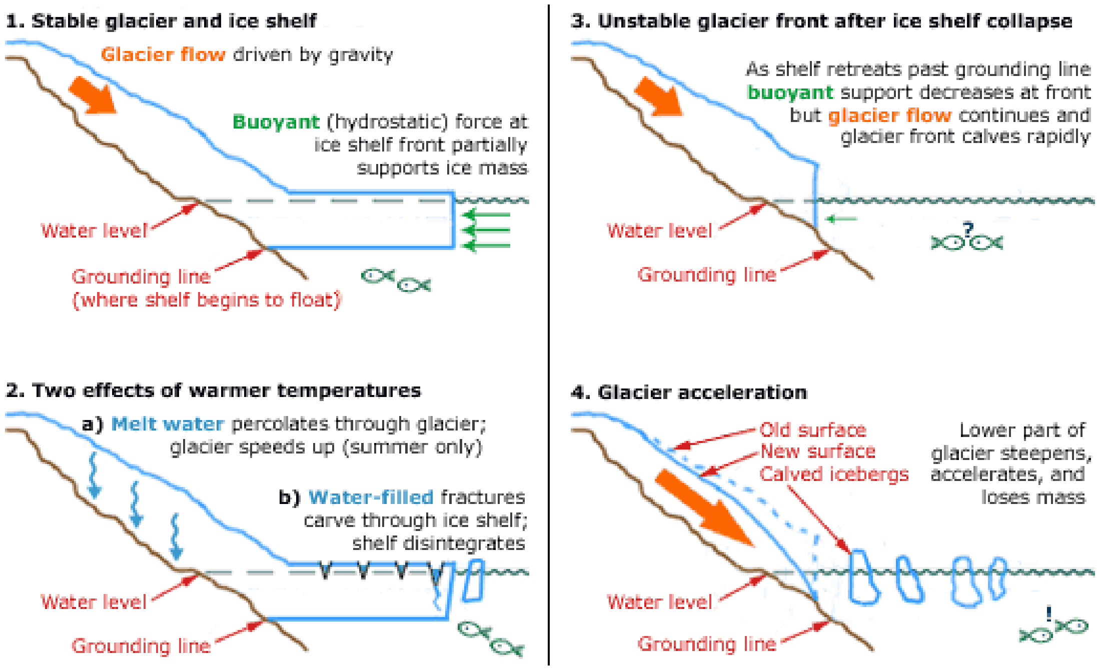


Figure 3.3 Ice Dynamics NSIDC[7] University of Colorado US (credit Rood, NSIDC[8], 2007 n.p.)

In Figure 3.3 four characteristic situations of ice movement have been described by Rood (2007):

- case 1: stable glacier and ice shelf. In the stable condition the ice shelf is grounded to the sea floor. The sea partly carries the combined weight of the ice and glacier. It falls with the tide. There is push back from the sea;
- case 2: effects of warmer temperatures. The glacier speeds up. The buttress loss speeds the flow of the glacier. The ice melts from the water below. The ice shelf disintegrates.
- case 3: unstable glacier front after ice shelf collapse. As shelf retreats past grounding line buoyant supports decreases at front but glacier flow continues. Glacier front calves;
- case 4: glacier acceleration. The lower part of glaciers steepens, accelerates and loses mass, producing calved icebergs. Large iceberg calving is one of the main causes of mass loss. According to the IPCC (2007 p.3):

> [t]he loss of seasonal snow and floating ice do not have a direct impact on global sea level, but acceleration of inland glaciers due to the loss of ice shelves (De Angelis and Skvarca, 2003; Rignot *et al*., 2004, 2005; Scambos *et al*., 2005), increases the runoff of

[7]National Snow and Ice Data Center
[8]http://www.wunderground.com/blog/RickyRood/archive.html?year=2007&month=02

melt water (Vaughan, 2006) and glacier acceleration will cause an increase in this contribution[9]".

Hansen (2007[10] p. 3) pointed out that: "[I]ce sheet disintegration, unlike ice sheet growth, is a wet process that can proceed rapidly. Multiple positive feedbacks accelerate the process once it is underway. These feedbacks occur on and under the ice sheets and in the nearby oceans". Under their own weight ice sheets deform and drag themselves outward. Once released icebergs can be classified depending on their shapes and sizes.

3.2 Icebergs Classification

Iceberg have been classified by the International Ice Patrol according to their size into six categories, as shown in Table 3.1.

Table 3.1 Classification Following the Size of Grand Banks Iceberg (data from U.S. Coast Guard Internat. Ice Patrol[11], 2007 and Timco *et al.* 2007 n.p.)

Nr	Size	Percentage (%)	Height (m)	Length (m)	Mass (T)
1	Growler	5.6	< 1	<5	500
2	Bergy bit	15.3	1…4	5…14	1,400
3	Small		5…15	15…60	100,000
4	Medium	15.3	16…45	61…122	750,000
5	Large	12.5	46…75	123…213	5 million
6	Very large	2.8	Over 75	Over 213	5 million
7	Size unknown	48.5			

Icebergs can adopt very unusual shapes, and consequently their movements are especially difficult to predict while they are melting. Their shape can be broadly classified as either tabular, which have steep sides and a flat top, or non-tabular, which can be dome, pinnacle, wedge, dry-dock, blocky or 'ice island' shaped. The profiles of icebergs of different sizes are given in Figure 3.4.

[9] www.ats.aq/documents/ATCM31/ip/ATCM31_ip050_e.doc
[10] http://iopscience.iop.org/1748-9326/2/2/024002/pdf/erl7_2_024002.pdf, see also http://iopscience.iop.org/1748-9326/2/2/024002/fulltext
[11] www.solcomhouse.com/iceberg.htm

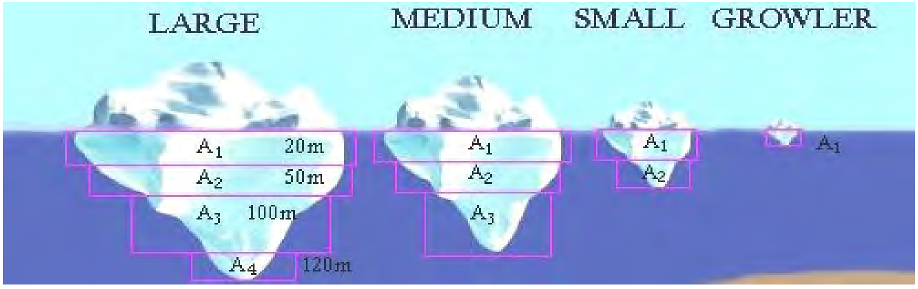


Figure 3.4 Icebergs of Different Sizes - Schematic Representation (Internat. U.S. Coast Guard Ice Patrol[12], 2007 n.p.)

According to Ocean Ltd (2004[13] p. 23):“[S]hape descriptions have changed over the years. Before 1980 four shape characteristics were used to describe icebergs (Marex, 1972)”. After 1980 Canadian Provincial Airlines Limited Environmental Services proposed a new classification of icebergs, and shape characteristics were defined according to eight types.Figures3.5 to 3.7 list old and modern icebergs shapes, as suggested by Ocean Ltd (2004) and refers to the general shape characteristics of the above water portion of the iceberg or its underwater shape.

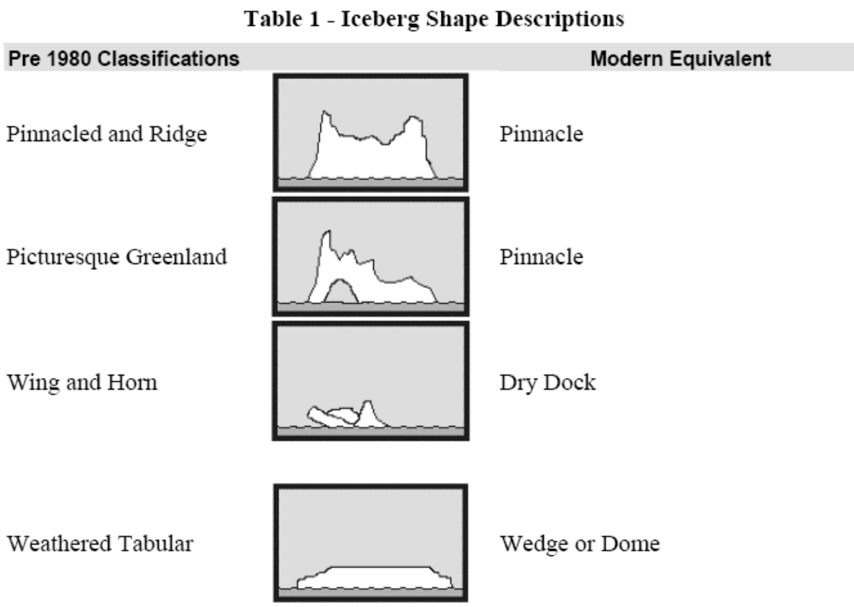


Table 1 - Iceberg Shape Descriptions

Pre 1980 Classifications		Modern Equivalent
Pinnacled and Ridge		Pinnacle
Picturesque Greenland		Pinnacle
Wing and Horn		Dry Dock
Weathered Tabular		Wedge or Dome

Figure 3.5 Old and Modern Terms used for Iceberg Shape Description above the Water Line (credit McClintock, McKenna and Woodworth-Lynas[14] PERD/CHC Report 20-75 Ocean Ltd June 2004 p. 24)

[12] www.solcomhouse.com/iceberg.htm
[13] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Oceans_Iceberg_Profiles_04.pdf
[14] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Oceans_Iceberg_Profiles_04.pdf

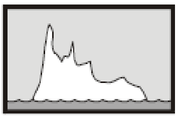
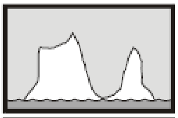
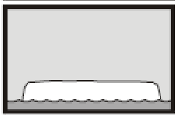
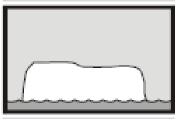
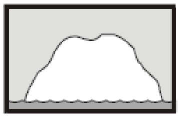
Modern Classifications		Description
Pinnacle		Large central spire or pyramid of one or more spires dominating shape. Less massive than dome-shaped iceberg of similar dimensions.
Dry Dock		Eroded such that large U-shape slot is formed with twin columns or pinnacles. Slot extends under the waterline or close to it.
Tabular		Horizontal, flat-topped with length-height ratio of 5:1 or more.
Blocky		Steep precipitous side with almost horizontal top and with length-height ratio of 3:1 to 5:1.
Dome		Large, smooth rounded top.

Figure 3.6 Icebergs Profiles above the Water Line - Modern Classification and Description (credit McClintock, McKenna and Woodworth-Lynas PERD/CHC 20-75 Ocean Ltd, 2004 p. 24)

Table 2 - Derived underwater shape classifications

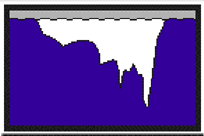
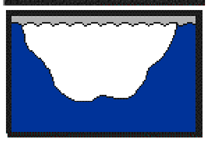
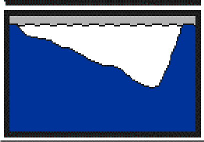
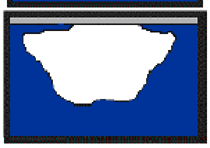
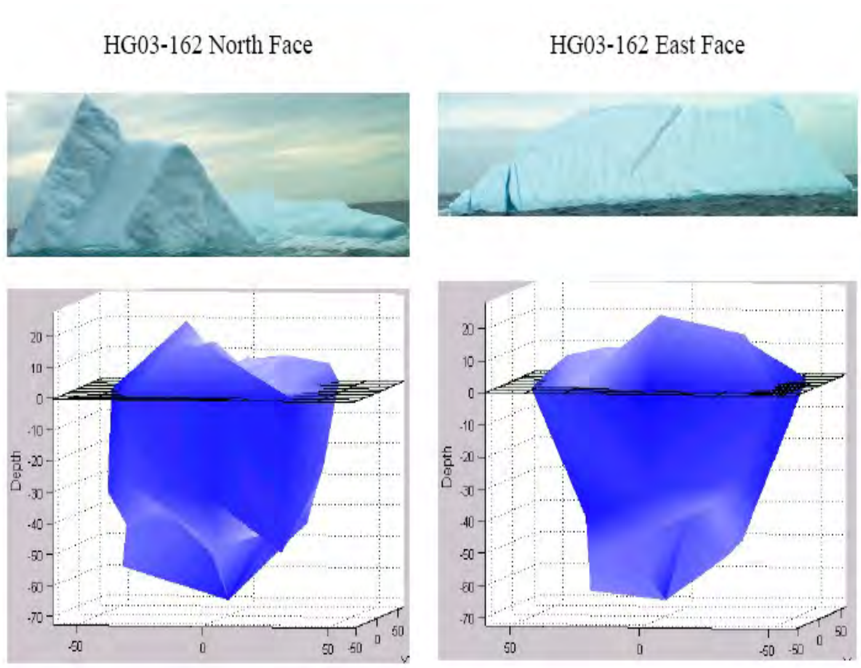
Classification		Description
Pinnacle		Large central spire or pyramid dominating the underwater shape.
Blocky		Steep precipitous side with almost flat bottom. Consistent with profiled large Tabular icebergs
Dome		Generally smooth rounded underwater profile.
Wedge		A below-water profile where the maximum draft is at or near one side of the iceberg.
Ram		Indicating large protuberances on one or more sides of the iceberg. Generally indicating a shallower maximum draft than the waterline length would indicate.
Tabular		Shallow, flat-bottomed. Consistent with profiles from Ice Islands. Large surface area, generally much shallower than the waterline length would indicate.

Figure 3.7 Icebergs Profiles below Water Line - Modern Classification and Description (credit McClintock, McKenna and Woodworth-Lynas PERD/CHC, Ocean Ltd, 2004 p. 30)

Icebergs classification by their visible shape is a standard procedure in most aspects of operational ice management. According to Ocean Ltd (2004 p. 25): “[T]hese classifications are used to identify icebergs. Mathematical functions of the icebergs shape classification are used to derive mass, draft and below-water surface area estimates”.

The underwater shape (Figure 3.7) of icebergs has been the subject of studies by Rossiter and Gustjaitis (1979), Walton (1987), Ocean Ltd (2004) and Canated *et al*. (1999). The underwater shape of icebergs is of the greatest importance as it influences the rate and direction of iceberg drift, off-shore structure and any potential collision which may occur between icebergs and other structures.

Iceberg shape characterisation has been a main topic for modelling using spatial statistics (McKenna, 2005; see also Appendix 4, Barker et al., 2004[15]). As a modelling example, the simulated profiles of two icebergs are presented in Figure 3.8.



[15]http://www.nrc-cnrc.gc.ca/eng/ibp/chc/reports/ice-engineering.html

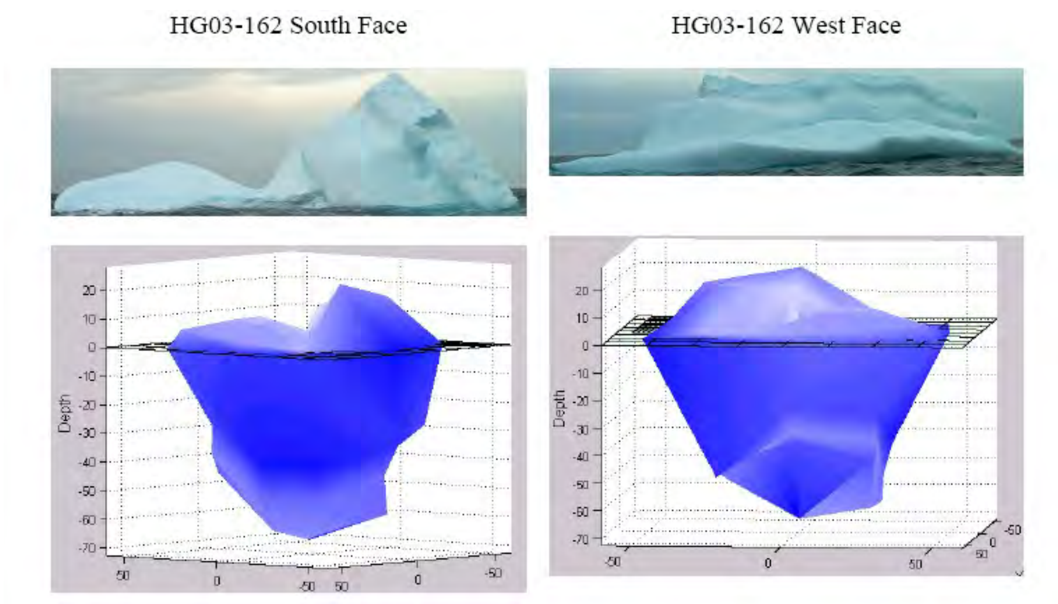


Figure 3.8 Icebergs Simulated Profiles (credit PERD/CHC[16], Report 20-75 McKenna, 2004 p. 20)

Modelling using spatial statistics has according to McKenna (2005 p. 10): "a high predictive capability that provides for the generation of a large number of complete icebergs shapes, each with statistical attributes of measured data". Iceberg shape data is studied to assess risk for offshore installations (Howard, 1986; Roche *et al*., 2004). Iceberg shape and their original dimensions mainly depend on glacier configuration and marine topography. No two icebergs are ever the same shape. An even more extraordinary variety of shapes results from the deterioration process of icebergs. At the extremity of the glacier the presence of cracks mark out future zones of tension that determine where iceberg calving will take place. Different types of calving exist, depending on the occurrence of cracking and fracturing, the state of the sea in the contact zone, the temperature of the sea and the ice, atmospheric conditions and the wave patterns of the ocean. Icebergs range in size from small icebergs to massive tabular and blocky icebergs over several billion tonnes depending on their origins.

3.3 Iceberg Properties

Chemical and physical properties of icebergs will be described.

16 ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Oceans_Iceberg_Profiles_04.pdfftp://ftp2.chc.nrc.ca/CRTreports/PERD/POAC_05_Iceberg_Shape_McKenna.pdf

3.3.1 Chemical Composition of Icebergs

As noted above, icebergs originate from glaciers. According to Haykin (1994[17] p. 44): “[U]nder the pressure of its own weight, the glacier flows from its high altitude source towards sea level”. Under the continuing action of tides and sea level changes due to the effects of wind and ocean swell, large pieces of ice break off as glacier tongues or ice shelves (Figure 3.9).

Figure 3.9 An Iceberg breaks off the Knox Coast in January 2008 in AAT
(credit Blackwood, Getty Images[18] 2008 n.p.)

Land icebergs, which fall from ice shelves, are usually composed of very pure ice water. Air bubbles within the ice structure reflect white light and explain the iceberg global white colour (Figure 3.10a).

Figure 3.10a White Iceberg (credit Dieckmann in Lee[19], 1990 p. 1968)

[17] http://books.google.com.au/books?id=1L8p6chyaYYC&printsec=frontcover&dq=Remote+sensing+of+sea+ice+and+icebergs+By+Simon+S.+Haykin&source=bl&ots=NlLKTbRERA&sig=DwBI0dL6g0PsUo1_qMtfpgMoAtA&hl=en&ei=jYAITYC7D4LWrQf39rnVDg&sa=X&oi=book_result&ct=result&resnum=1&ved=0CBUQ6AEwAA#v=onepage&q&f=false

[18] www.msnbc.msn.com/id/30058284

Sometimes land icebergs are blue, green (Figure 3.10 b, c and d), black or brown, with mud or stone layers inside (Wordie and Kemp, 1933; Binder, 1972; Fletcher, 1984).

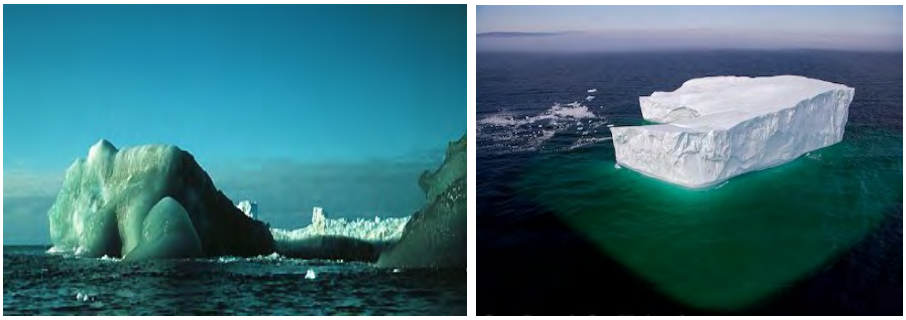


Figure 3.10b and c Green Iceberg Weddell Sea, Antarctica (credit Dieckmann in Lee, 1990 p. 1867) Large Iceberg Newfoundland, Canada, Atlantic Ocean (credit Hicker[20], 2005 n.p.)

Figure 3.10d Blue Iceberg (credit Hollocher[21], 2001 n.p.)

The melted water of blue ice or clear icebergs is generally free of bubbles as it refreezes and fills in crevasses formed in the creeping glaciers. Bubble-free ice has a blue colour. According to Bruneau (2010[22] n.p.):

> The ice is blue because of the natural light scattering characteristics of pure ice. Occasionally, airborne dust or dirt eroded from land ends up on the glacier surface. This eventually leads to the forming of a darkened brown or black layer (in any orientation) within the ice of a floating iceberg. (…) Sometimes airborne dust from volcanic eruptions

[19] http://www.usna.edu/Users/oceano/raylee/papers/RLee_JOSAA_green_icebergs.pdf see also http://www.usna.edu/Users/oceano/raylee/RLL_cv.html
[20] http://www.hickerphoto.com/aerial-iceberg-underwater-picture-atlantic-ocean-21505-pictures.htm
[21] http://minerva.union.edu/hollochk/skaergaard/landscape/ice.htm
[22] http://www.caperace.com/stories/where-do-icebergs-really-come-from/ and http://www.provincialairlines.com/ESDIcebergs.htm

> or from the wind (thousands of years ago) is deposited on the surface of a glacier and gradually becomes trapped within the ice so that traces are found in icebergs.

Gas as carbon anhydride, chlorides, sulphates, nitrates, carbonates, metals (steel, iron, manganese) and micro organisms are usually found within an iceberg (Dieckmann *et al*., 1987). Dust and salt water can be found within the superficial layer of the ice. Icebergs often contact and become grounded on the seabed. This happens more frequently along the coast where changing tidal currents and high winds move icebergs to shore.

3.3.2 Physical Properties of Iceberg Ice

The physical properties of iceberg ice have been extensively described by Paterson (1997). Based on physical properties (density, mechanical, electrical and optical properties) of icebergs ice different non contact detection techniques can be developed. As an example, see Synthetic Aperture Radar (SAR) imagery which has been developed for the prediction of the icebergs drift or decay and of the dynamics of air-sea-ice processes. Images of icebergs are shown in Figures 3.11.

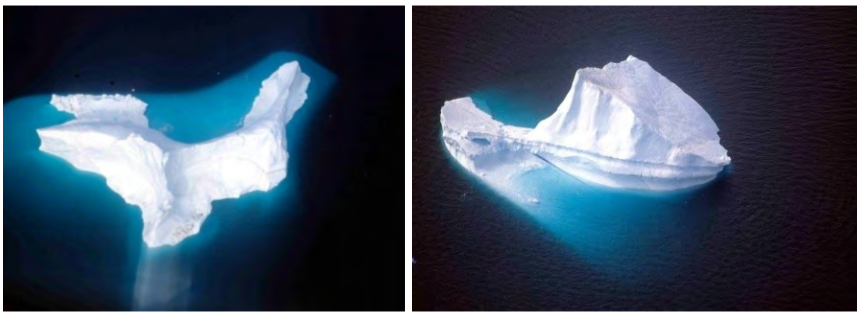


Figure 3.11 The Iceberg 2 and Iceberg 4 1997 08 07 near the North-Eastern Coast of Baffin Island (credit Walk, 1997[23] [24], Creative Common Attribution Share Alike 2.5 Generic n.p.)

According to Rossiter *et al.*, (1979 p. 99):

> The measurement of iceberg underwater dimensions and features will be essential for safe and effective choice, preparation, and transportation of icebergs. An iceberg's subsurface shape affects its deterioration, its form drag, and its strength. Short-pulse radar echo-sounding methods can be used to sound icebergs since polar ice is highly

[23]http://commons.wikimedia.org/wiki/File:Iceberg_2_1997_08_07.jpg
[24]http://commons.wikimedia.org/wiki/File:Iceberg_4_1997_08_07.jpg

transparent to radio signals. Available radar equipment can be used either from an aircraft or from the iceberg surface, and can provide reliable, easily-interpreted, real-time results.

In what follows, the physical properties of icebergs ice such as density, mechanical, electrical and optical properties will be described.

3.3.3 Density of Iceberg Ice

The density of icebergs ice is a parameter used for multiple purposes such as iceberg shape modelling, the calculation of the centre of iceberg mass and buoyancy, the calculation of the inertia of the iceberg, "the relationships between waterline length or width, height, draft and mass" (McKenna, 2004 p. 555[25]) of icebergs, the relationships between mass and index dimensions, the development of a tool for use in probabilistic simulations or the prediction of performances of a structure or vessel (Abdelnour *et al.,* 1992). According to Kelly (1996 p. 1): "[E]stimates of the flux of icebergs can be achieved by obtaining separate estimates of iceberg ice densities and of drift patterns of iceberg velocities". The density of iceberg ice is not uniform and depends on the location and composition of the superficial layers (air bubbles can represent up to 50% of the volume). A newly calved iceberg retains, in general, the physical properties and the density of its original ice shelf, which has the same layered structure as the continental ice sheet from which it flowed. Layers composed from freshly fallen snow are underlain by older annual layers having a higher density. The layered structures of tabular icebergs appear on their vertical (Figure 3.12).

Figure 3.12 Tabular Iceberg (credit Lordcrimson, 2007 wordpress.com[26], n.p.)

[25]ftp://ftp2.chc.nrc.ca/CRTreports/PERD/POAC_05_Iceberg_Shape_McKenna.pdf
[26]http://lordcrimson.files.wordpress.com/2007/10/iceberg.jpg

The freeboard of the iceberg is composed of compressed snow of relatively low density compared with old ice density. The density of iceberg ice (910 kg/m³) is very similar to the density of pure ice (Comfort *et al.*, 1999 p. 16). Pure ice is near to 920 kg/m³ in density and sea water is about 1025 kg/m³. The ratio between these two values is 0.89. Large tabular icebergs float typically only one-ninth of its volume above water. This can be attributed to the difference in density between iceberg ice and sea water. According to Kelly (1996 p.1): "[T]he most comprehensive data set regarding the ice densities for icebergs of varying sizes was compiled by the International Ice Patrol starting in 1960"[27].

3.3.4 Mechanical Properties of Iceberg Ice

The mechanical properties of icebergs ice are key parameters for modelling icebergs drift and decay, icebergs transportation and buoyancy, and icebergs loading terminals (Bigg *et al.*, 1997). The mechanical properties of iceberg ice have been reported by Lewis and Edwards (1970), Gammon *et al*. (1983; 1985), Gagnon and Gammon (1994) and more recently by Barrette and Jordan (2001). Barrette and Jordan (2001[28]) found that iceberg ice harvested in spring 2000 had a bending strength of between 1.0 and 3.0MPa. The corresponding grain size was between 25 and 175mm² and the number of air bubbles/mm² ranged between 0.5 and 3.3. The internal structure of ice affects the mechanical behaviour of icebergs and the crystal size and the amount of air have an effect on failure strength. A large amount of bubbles leads to lower strength values. El-Tahan *et al*. (1984, 1985) studied the uniaxial compressive strength by undertaking impact tests on icebergs. The results are given in Table 3.2. Depending on the strain rate during the tests, the mean compressive strength, at -5°C, is reported between 6.6 and 7.4MPa.

Table 3.2 Uniaxial Compressive Strength of Iceberg Ice at -5°C, Strain Rate Range 10^{-4} to 10^{-1} s^{-1} (credit El Tahan *et al*., 1984 p. 5)

Mean strain rate (s^{-1})	Mean strength MPa	Mean tangent modulus of elasticity GPa	Mean time to failure (s)	Mean strain at failure (%)
0.82×10^{-3}	7.43	3.04	3.38	0.19
0.59×10^{-2}	6.6	3.97	0.20	0.12
0.58×10^{-1}	6.97	6.7	0.02	0.11

[27] http://www.uscg-iip.org/General/database.shtml
[28] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Fracture_01.pdf

Figure 3.13 shows the variation of the uniaxial compressive strength for iceberg ice and for laboratory grown freshwater ice as a function of strain rate. It is an important factor for experiments modelling icebergs of operation (Sassolas, Pfeffer and Amadei, 1996).

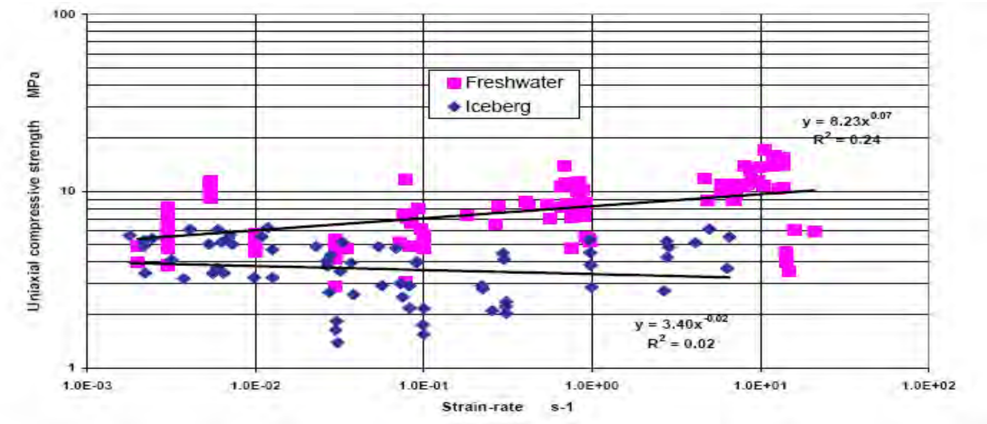


Figure 3.13 Uniaxial Compressive Strength (MPa) of Ice from Icebergs and Freshwater Ice as a function of Strain Rate (s^{-1}) (credit Jones, 2006 p. 10)

Jones (2006[29] p. 13) noted that:

> [t]he strength of iceberg ice is less than freshwater ice, laboratory grown ice or natural ice. At -10°C and at a strain-rate of 10^{-3} s^{-1}, typical of ice-structure interaction, iceberg ice has 1.7 times less strength than other freshwater ice. This difference increases to three times less strength at the highest strain-rates tested (10^{-1} s^{-1}). This difference is probably due to the presence of pre-existing cracks and flaws in iceberg ice. At very low strain-rates (below 10^{-6} s^{-1}) there is no difference in the strength of iceberg ice [in comparison with other sources of freshwater ice].

The mechanical properties of icebergs explain other aspects of iceberg activity, including their structural characteristics such as stability, and thermal properties, such as melting patterns (Weber and Nixon, 1997).

3.3.5 Dielectrical Properties of Iceberg Ice

Icebergs physical and dielectric characteristics determine radio waves penetration rates. The dielectrical properties of icebergs have been used for more than one decade for iceberg

[29] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Iceberg_Strength_06.pdf

location and tracking through scatterometer images. The observed backscatter is a function of the dielectric properties of the surface as well as the roughness and geometry of the inspected zone. Dielectrical properties of icebergs exhibit a high contrast with the surrounding ocean and thus icebergs are easily identified in scatterometer images, as can be seen in Figure 3.14.

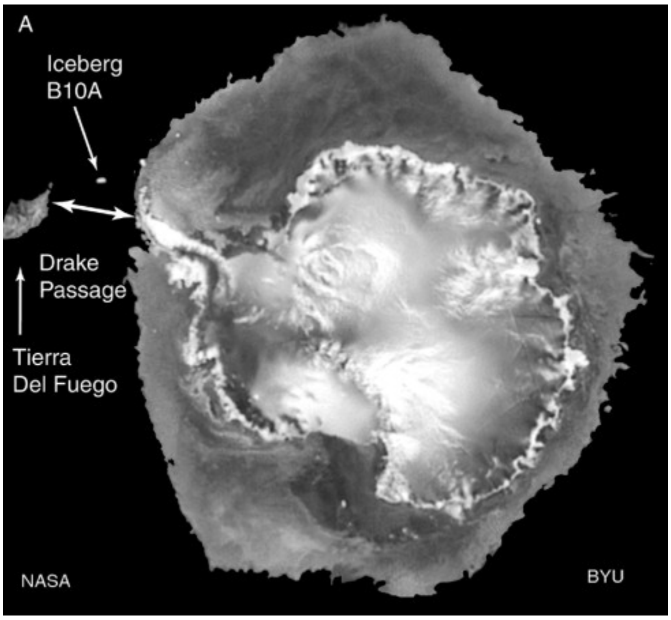


Figure 3.14 Antarctica and Surrounding Sea Ice Cover in July1999 with QSCAT image. Iceberg B10A (50 km x 100 km) is identified in Drake Passage (credit Long *et al*., 2001 p. 11)

The dielectrical properties of glacial ice include relative complex dielectric permittivity expressed by the dielectric constant and the dielectric loss. These dielectrical properties have been examined over the last 50 years through laboratory and *in situ* measurements conducted by a number of researchers (Pearce and Walker, 1967; Page and Pamseimer, 1975; Kirby and Lowry, 1979; Haykin *et al*., 1994). Dielectrical properties depend on several factors such as the measurement frequency (MHz or GHz range), ice temperature, and ice density.

Moreover, the parameters measured by radar depend on the electromagnetic properties of ice. Since icebergs that originate from glaciers are not saline, relatively low dielectrical properties can be expected. Kirby and Lowry (1979) report the relative complex dielectric permittivity of icebergs equal to 3 at 10 GHz frequency. Pearce and Walker (1967) examined icebergs with a density of 920 kg/m^3 and measured a dielectric permittivity of 3.31 ± 0.04 at 30MHz. Jezek *et al*. (1978) reported values for dielectric permittivity of iceberg ice between

3.89 and 3.09. These values were measured *in situ* by radar wide-angle reflection. At frequencies greater than 1 GHz, Page and Pamseimer (1975) reported a loss tangent equal to 2 x 10^{-3}. Table 3.3 summarises some of the dielectrical properties of iceberg ice in comparison with sea ice, snow and seawater, at 100 MHz.

Table 3.3 Dielectrical Properties of Iceberg, Snow and Seawater at 100 MHz (credit Haykin *et al.*, 1994 n.p.)

Ice type	Typical thickness (m)	Dielectric constant (no units)	Attenuation (dB/m)
Young ice	< 0.5	6	> 100
First year	0.5 - 3.5	4 - 6	5 - 10
Old ice	1 - 10	3.5 - 4.5	0.1 - 10
Iceberg	< 10	3.2	0.1
Snow	< 1	2 - 3.5	0.01- 0.1
Sea water	-	80	100

A basic knowledge of the dielectrical properties of iceberg ice is required for the detection of icebergs. Several research programmes operate satellite radar detection systems in order to identify icebergs (Table 3.4).

Table 3.4 Research Projects on Icebergs Satellite Radar Detection

Program	Reference	Notes
ADRO 1997/1998	Randell *et al.*, 1999 and 2000	RADARSAT one - fine mode iceberg detection - ground truthing off Newfoundland and Antarctica
ADRO 1999	Flett *et al.*, 2000	RADARSAT one range of scansar and wide resolution modes- ground truthing off Newfoundland - some data on ship discrimination
ADRO-2, CIS 2000	Power *et al.*, 2001	RADARSAT one range of scansar and wide resolution modes- ground truthing off Newfoundland - some assessment based on wind speed and look angle
ADRO &CIS, ENVIRSAT 2003	Lane *et al.*, 2003	RADARSAT one & ENVISAT assessment based on wind speed and look angle
CIS/IIMI 2003/2004	Howell *et al.*, 2004 and 2006	RADARSAT one & ENVISAT effect of polarisation in ship/ ice discrimination
CIS GMES 2005	C-CORE, 2005b	ENVISAT ship - iceberg discrimination
Barents Sea 2003	C-CORE, 2006a	ENVISAT - ground truth ship and icebergs - inexact ground truthing hence correlations uncertain

3.3.6 Optical Properties of Iceberg Ice

The determination of the optical properties of iceberg ice is a problem of atmospheric optics as discussed by Bohren (1983) and Lee (1990). Trapped air bubbles in most iceberg ice make it white. According to Lee (1990 p. 1):

> [P]ure homogeneous ice has an absorption minimum at 470 nm in the visible spectrum. If white light is transmitted through a section of pure ice 1 m thick, the resulting dominant wavelength is 490 nm…Translucent green icebergs might be caused by some colorants, but samples taken from those icebergs contained little green material.

Lee (1990) developed remote-sensing techniques that involved using colour slides to analyse the optical properties of green icebergs. He argued that ice intrinsic optical properties and the reddening of daylight at a low sun angle produce the colours observed.

3.4 Location of Iceberg Resources

Icebergs that originate from Antarctica have specific characteristics.

3.4.1 Iceberg Names

The National Ice Centre (NIC) in the USA is the organisation that gives names and follows Antarctic icebergs. It uses polar orbiting satellites to survey the Polar Regions. In Antarctica, iceberg names correspond to the Antarctic regions from where they are first located (for example: iceberg A-23A, where A = the Weddell Sea). The NIC records the initial detection of an iceberg and records its original location.

3.4.2 Antarctic Region

Ninety per cent of the world’s ice volume and 70% of the world's fresh water are found in Antarctica, mainly in the east Antarctic ice sheet, limited by Transantarctic Mountains (Figure 3.15).

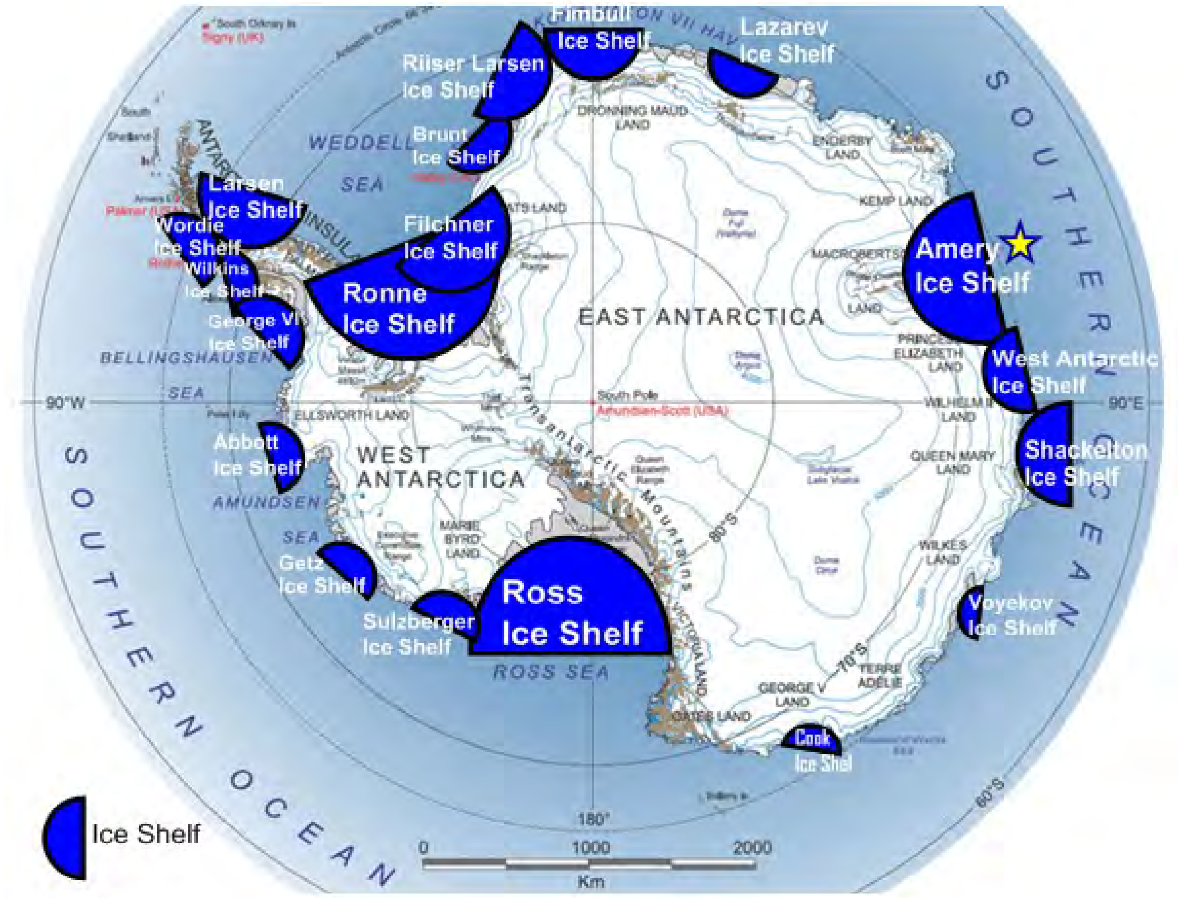


Figure 3.15 Ice Shelves in Antarctica (credit from Landsat Image Mosaic of Antarctica[30] 2003 n.p.)

Antarctica has a global area of 14,000,000 km². About 98% of Antarctica, is covered by the Antarctic ice sheet, which represents 13,720,000 km² and has an average thickness of 1.6 km (CIA, 2010[31]). An interesting feature of the submarine topography off Antarctica is the occurrence of an inner shelf depression up to 1,700 m deep, separated from the outer continental shelf by sills about 500 m deep. On the base of the continental sheet, lies a plain with depths ranging from 3,700 to 5,000 m, while the South Sandwich Trench descends to 8,620 m. Most of the Antarctic coastline is buried under ice flowing over the continental margins. Littoral regions are common on the west coast of West Antarctica and the islands of the Scotia Arc, but rare in East Antarctica. In Antarctica the continental shelf break occurs on average at about 400 m deep, while in the Ross Sea it is up to 800 m deep. Visible areas of shoreline may be abraded by fast ice pack, brash ice and bergy bits, which may scour the littoral region to a depth of 15 m. The local characteristics of the shore determine the

[30] from http://79south.blogspot.com/
[31] https://www.cia.gov/library/publications/the-world-factbook/geos/ay.html#People

duration of ice cover. Fast ice and pack ice affect the majority of continental shores for more than six months a year, and in the Ross Sea fast ice persists for 11 months a year. In the Southern Hemisphere the sea ice extent varies from 3 million km² in February to 20 million km² in September (Gloersen *et al*., 1992). According to Hughes (2009 n.p.):

> Most of the discharge of the West Antarctic Ice Sheet happens via the major ice streams entering the Ross Ice Shelf, the Rutford Ice Stream entering the Ronne and Filchner shelf of the Weddell Sea and the Thwaites Glacier or the Pine Island Glacier entering the Amundsen Ice Shelf.

In Antarctica, beyond the yearly variability of iceberg distribution, it appears that icebergs are mainly produced in summer in the Ronne Filchner Ice Shelves zones, in the Amery Ice Shelf zone, and at a smaller degree in the Ross Ice Shelf zone. From October to March the iceberg concentration is important in the Ronne Filchner Ice Shelves zones, in the Amery Ice Shelf zone (Figure 3.16).

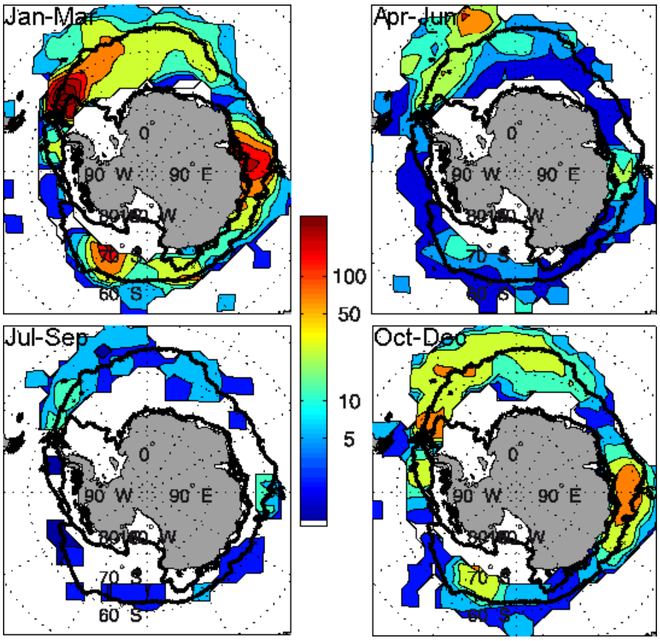


Figure 3.16 Number of Iceberg around Antarctica Deduced from Computer Models; colour scale: red 100 icebergs, orange 50 icebergs, blue green 10 icebergs, blue 5 icebergs (credit *Ifremer* - French Institute for Sea Research, n.d.n.p.)

In summer time (January to March), more than 100 icebergs are calved in the Weddell Sea, Ross Sea and Ronne-Filchner Ice Shelf. In winter time (July to September) less than 10 icebergs are calved. The icebergs drift more from April to June. The calving begins to increase in spring, from October to December. Large tabular icebergs originate in the Weddell and Ross Seas (Gladstone and Bigg, 2002). In particular a region of interest for iceberg transportation projects is the Amery ice Shelf (AIS) located around 71° S, 70° E in East Antarctica between the Australian stations of Davis and Mawson (Janssen and Rachael, 2008[32]). The Lambert Glacier Basin system supports the AIS (Allison, 1991; AAD, 2011[33]). With 60,000 km^2, it represents a major ice shelf in East Antarctica and is the third largest ice shelf in Antarctica (Budd *et al.*, 1967). The calving front is about 550 km long. When analysing the balance of the AIS, it appears that most of the lost occurs through basal melting processes and icebergs calving production 44.6 +/- 9.3 Gt per year (Young and Hyland, 2002; Galton-Fenzi *et al.*, 2009; Figure 3.17).

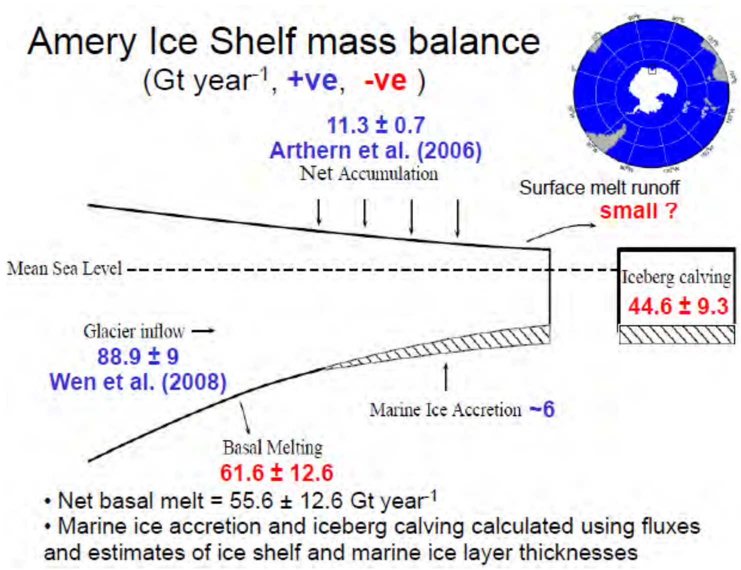


Figure 3.17 The AIS Mass Balance (credit Galton-Fenzi *et al.*, 2009[34]).

Large iceberg discharges occur on a 60 year cycle basis (Coleman and Young, 2003): in 1963/1964 a 10,000 km^2 iceberg broke off and recently in the years 2000s a 500 km^2 tabular iceberg was breaking off.

From the AIS, icebergs naturally go about 1,700 km south-southwest of WA, north of 56 degrees south. However sometimes they can get closer as in 2009 when a 20 billion tonne iceberg B17B (19 km long and 8 km wide), arrived at 48.8º S and 107.5º E. This

[32] http://eprints.utas.edu.au/8081/1/Janssen%26Hurd_2008_author_version.pdf
[33] http://www.antarctica.gov.au/about-antarctica/fact-files/climate-change/ice-shelves
[34] http://neptune.gsfc.nasa.gov/wais/pastmeetings/PPT09/Galton-Fenzi.pdf

iceberg calved from the Ross Ice Shelf 10 years before stayed for about five years close to the Mertz Glacier and drifted through currents and winds around Antarctica for five more years. Recently in 2006 and 2009 2 billion tonnes iceberg originating from the Ronne or the Ross Ice shelves passing off Australia's Macquarie Island and naturally drifting to New Zealand coasts were spotted (Figure 3.18a and b).

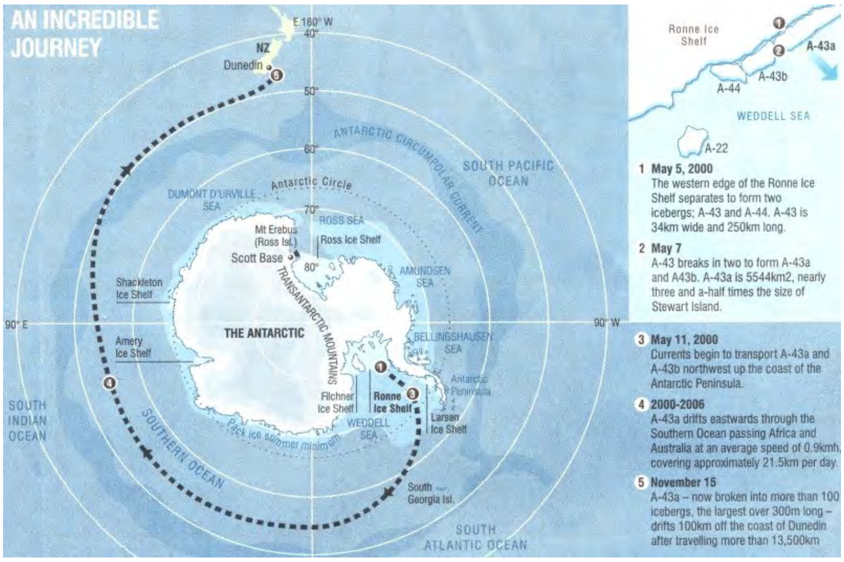


Figure 3.18a Iceberg Drift (13,500 km) from Ronne Ice Shelf to New Zealand (credit Helicopters Otago Ltd. 2006[35] n.p) Legend: A group of 200 tabular icebergs arrived from the Ronne Ice Shelf in the Weddell Sea to the South East coasts of New Zealand in November 2006

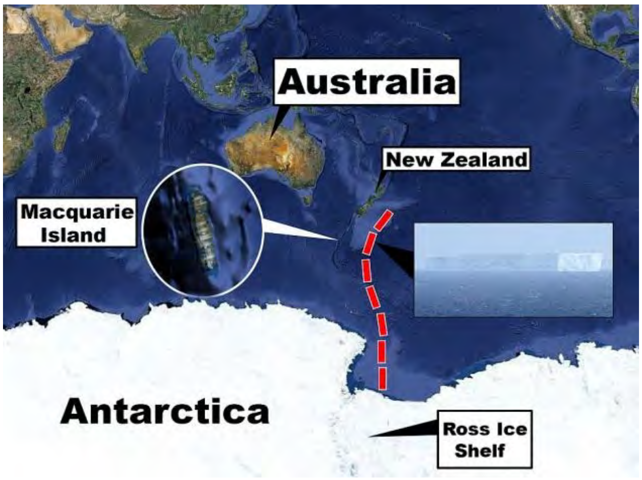


Figure 3.18b iceberg Drift (13,500 km) from Ross Ice Shelf to New Zealand (credit Dailymail[36], 2009)

[35] www.newzeal.com/theme/heli/IcebergMap.jpg
[36] http://www.meteorologynews.com/2009/12/15/huge-icebergs-drifing-toward-australia-new-zealand/, http://www.dailymail.co.uk/news/article-1227228/Giant-iceberg-spotted-Australia.html

The icebergs are carried northward and westward at up to 8 km/day in the Easterly wind and currents around the continent until they reach the Antarctic Convergence, where they melt rapidly in warmer water. The icebergs are present in a band from 150 to 300 km from the Antarctic costs, particularly in the Weddell Sea and in the Ross Sea, near the Kerguelen Islands, flowing in the Western currents of circumpolar ocean. They are moved by the western currents of the Southern Ocean and for a transportation from the Amery ice shelf located in the AAT to WA, these currents are favourable. From the Weddell Sea they reach South Africa, Argentina, Australia or New Zealand and usually melt between 58° to 63° S (Figure 3.19a).

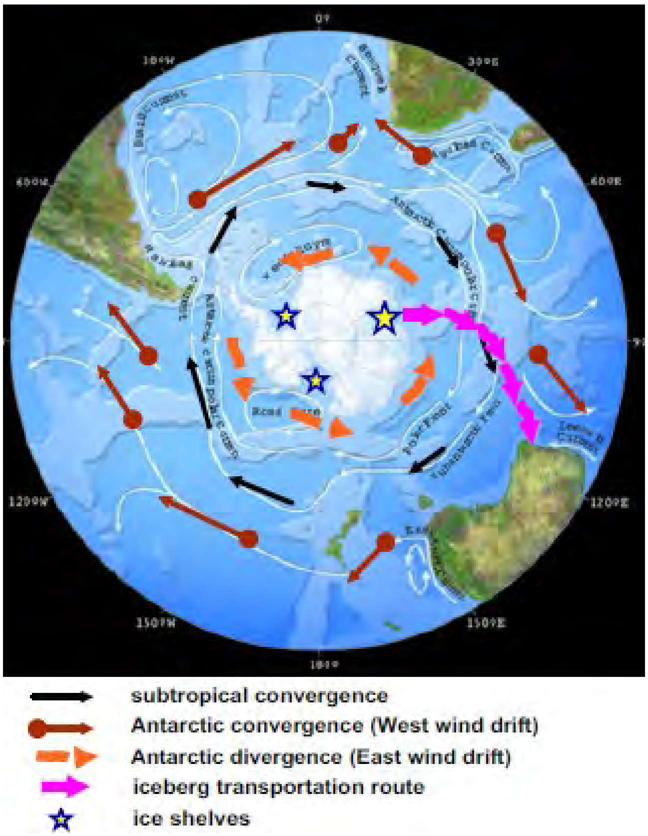


Figure 3.19a Antarctic Circumpolar Currents (credit from Antarctica cup[37] n.d. n.p.)

These types of event are rare even if Tasmanian Aboriginal legends evoke "white islands" floating (Young in AAD, 2009[38]). For the iceberg transportation project studied in this thesis

[37] http://www.antarcticacup.com/images/currentsxl.gif see also GRID, New-Zealand, UNEP, 1997http://maps.grida.no/go/graphic/the_antarctic_convergence, AAD, 2010 http://www.antarctica.gov.au/about-antarctica/fact-files/geography/antarctic-convergence and Rintoul *et al.*, 2001 p. 272 http://epic.awi.de/Publications/Rin8888b.pdf

the region of iceberg capture being around 2,000 km away from WA, the iceberg concentration is relatively high and about 100 of large icebergs per year can reach this zone. However their origins, sizes, shapes and states vary. In this zone, icebergs mainly come from the Ross, the Ronne or the Amery ice shelves and generally head towards the ACC with more southerly path ways (Figure 3.19b). This figure will be later used for transportation analyses to put them in parallel with icebergs natural pathways.

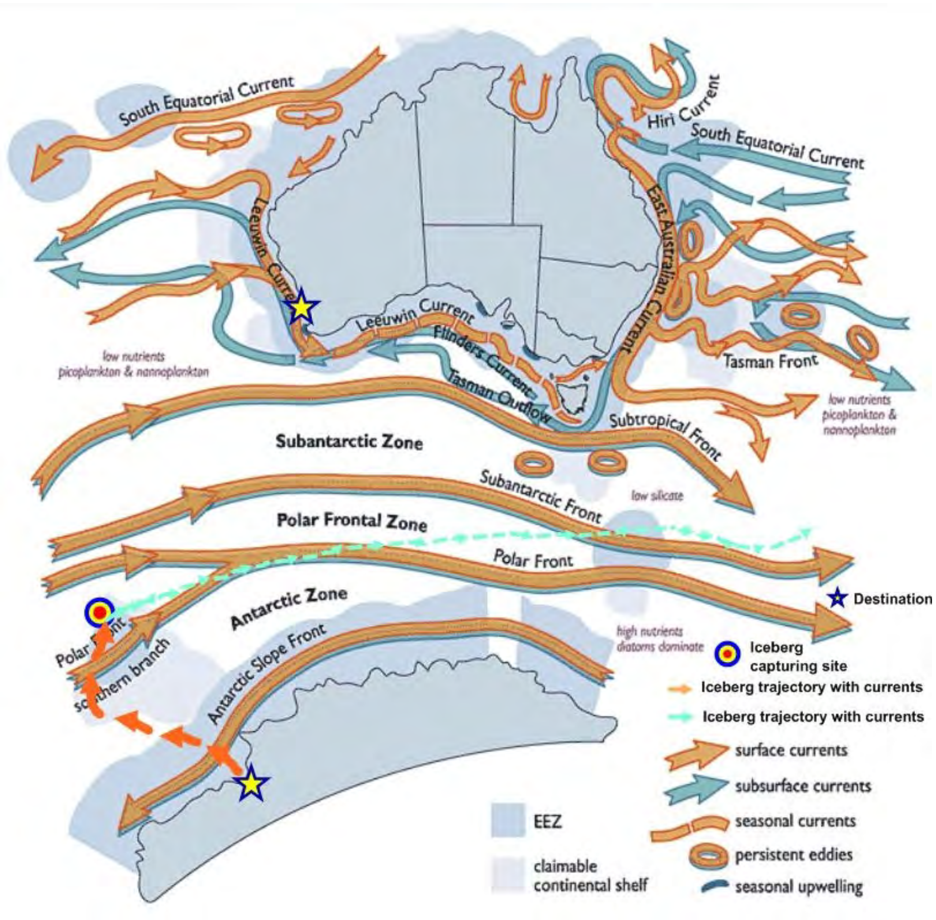


Figure 3.19b The Major Ocean Currents in the Australian Region (credit from Edmonds, 2007[39] n.p.)

In details, the AIS currents circulation is characterised by a ice front circulation 72.5° 8 and 74.08E which splits into a weak north eastern gyre of 72.08° E under the ice shelf, and continues to an east circulation (70.78° S, 70.48° E) and a strong main gyre 70.08° S, 71.08° E (2.8-Sv), to the west with southern gyre centred at 71.68° S, 69.88° E. regions of freezing,

[38] http://www.antarctica.gov.au/media/news-archive/2009/giant-iceberg-heading-towards-australia, http://www.theaustralian.com.au/news/nation/giant-iceberg-heading-for-western-australia/story-e6frg6nf-1225808821794

[39] www.waterengineeringaustralia.com.au/pdf/wea_0809.pdf

in the northwest corner of the domain, and around 69.88° S, 69.98° E (Warner and Budd, 1998; Williams, Warner and Budd, 2002[40]).

3.4.3 Antarctic Specificities

Unlike the Arctic, much of the Antarctic continent is 3 km above sea level, and since temperature decreases with elevation this makes the formation of ice in the Antarctic subject to much colder conditions than in the Arctic. Antarctic ice sheets expand by gravity and break off reaching the coasts in the form of icebergs or ice shelves (IPCC, 2007[41]). Antarctic sea ice shows little surface ablation and rarely, if ever, exhibit melt ponds. The surface albedo of Antarctic sea ice is similar to that of snow-covered ice throughout the year. The main difference between the ablation seasons in the Arctic and in the Antarctic results from differences in the meteorological parameters driving the surface energy budget. In spring, Antarctic surface winds are 60 to 100% stronger than Arctic winds (Parish and Cassano, 2003). The magnitude of the turbulent transfer may preclude surface melting in the Antarctic. Relatively dry winds off the continent (7 to 10 m/s) lead to a relative humidity in the surface layer over Antarctic sea ice that is generally 60% or less. In comparison, springtime humidity over Arctic sea ice is higher than 75%, with spring winds over 4 to 6 m/s. In the Antarctic the atmospheric humidity enhances turbulent surface transfer. According to Andreas and Ackley (1981 p. 1): "[L]ow relative humidity associated with dry winds and an effective radiation parameter smaller than that which is characteristic of the Arctic are primarily responsible for the absence of melt features in the Antarctic".

Antarctic sea ice melting begins when the surface-layer air temperature is above 0°C, which is rarely the case over Antarctic sea ice (Andreas and Ackley, 1982). The observations on sea ice by Andreas and Ackley would suggest that mass losses could be more controlled by sublimation and rapid evaporation. In Antarctica, the wetness of snow or ice is constant throughout the snow cover for air temperatures between -12°C to -5°C without the presence of slush (Wadhams, 1986).

For all these reasons, Antarctic iceberg stability and melting features are more suitable for an iceberg transportation project than one based in the Arctic. Icebergs can be operated from precise regions which will produce more regular volumes.

[40] journals.ametsoc.org/doi/pdf/10.1175/1520-0442(2002)015%3C2740%3ASOTAIS%3E2.0.C0%32B
[41] http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch4s4-6-2-2.html

3.5 Volume and Size of the Antarctic Iceberg Resource

There are several methods available for evaluating the size of the iceberg resource in Antarctica. These methods include measuring the number of icebergs produced as well as the annual volume of ice produced. It is easier to evaluate the annual volume of ice rather than the number of icebergs, as any individual iceberg can fracture to produce several new ones. Icebergs are far more abundant in the Antarctic than in the Arctic. Over 90% of the world's mass of icebergs is found in the Southern Ocean (Hult and Ostrander, 1978). As a freshwater source, Antarctica represents 35 million km^3 of pure water (Hult and Ostrander, 1973). Loewe (1967) calculated Antarctic iceberg production rate as $1.3x10^3$ km^3/year. This assumption is deduced from mass equilibrium considerations, based on mean annual precipitation map, 0.3 5 m ice/year (Budd *et al.,* 1971). The precise amount of ice discharge from Antarctica each year is not known, but a Soviet survey conducted in 1965 counted about 30,000 icebergs in an area of 4,000 km^2 between longitude 44° E and 168° E (Shilnikov, 1965). In total these icebergs had an estimated volume of 3,165 km^3. According to Hult and Ostrander (1973), the annual yield of iceberg could be about 1,200 km^3 and the total accumulation in the Antarctic Ocean about 7,000 km^3. Annually, the Antarctic continent receives between 10 and 30 cm (1,500 to 4,500 km^3) of water as precipitation, and more than half of this water is calved into icebergs of various sizes (Shepherd and Wingham, 2007). Orheim (1980; 1985; 1988) has estimated that at any one time there are up to 200,000 icebergs in the Southern Ocean south of the Antarctic Convergence. Around 2,500 billion tonnes of snow annually accumulate on average in Antarctica. Jacobs *et al*. (1992) reported that iceberg calving events from the Antarctic ice shelves occur regularly and amount to about 2,000 Gt/year. Based on those figures, annual iceberg production would cover the world's water consumption for more than six months.

There is a large range of iceberg sizes. These icebergs range in size from 50 m long up to kilometres in length. According to Hult and Ostrander (1973), icebergs as large as 70 m in height and up to 350 km long are falling from the Ice Cap.

According to Young (2001 AAD[42], p. 25):

> Mean annual air temperatures on the ice shelf fronts, between latitudes of 75° S and 78° S, are around -20°C, and summer air temperatures rarely reach melting point. Ocean

[42]http://www.antarctica.gov.au/__data/assets/pdf_file/0014/21182/p24_25_science.pdf

> temperatures are at or close to freezing throughout the year. Calving of ice from any section of the front of an ice shelf may occur frequently and produce a few or many small icebergs, or occur rarely and produce one or a few very large icebergs … By way of contrast to these 'normal' events, there has been a dramatic decrease in the area of relatively small ice shelves fringing the Antarctic Peninsula over several decades

For the whole of Antarctica, very large icebergs can be regularly released on a decennial basis (Gladstone and Bigg, 2002). Ice islands are relatively rare in the Arctic but common in the Antarctic where massive icebergs can easily be 200 m thick, having a freeboard of about 40 m and a length of many kilometres (Husseiny, 1978). The icebergs in Antarctica are the largest in the world; for example in 1956, an iceberg covering 31,000 km^2 was released from the Ross Ice Shelf. The Ross Ice Shelf released again in 1987 a 6,350 km^2 iceberg with an estimated volume of 1,400 km^3. In recent years, several large Antarctic icebergs have been calved from the Ross Ice Shelf and the Ronne Ice Shelf. Icebergs over 80 km long regularly calve from Antarctic ice shelves (Hughes, 1972; Denton and Hughes, 1981; Stone 1993). In March 2000 an iceberg 295 km long by 37 km wide (known as B-15A) calved from the Ross Ice Shelf (Figure 3.20).

Figure 3.20 Tabular Iceberg B-15A 160 km long (credit Landis AFPNSF world news[43], 2001 n.p.)

The different pictures of tabular icebergs give an idea of the size scales and shape variety of tabular icebergs. Since 2007, the Ross Ice Shelf released large icebergs B16, B17, B18,

[43] Shapinski http://www.cyberchill.org/

B19 and C16. On the other side of Antarctica, three giant icebergs calved from the Ronne Ice Shelf in 2007 A 22 (49 km by 23.4 km), A43 (250 km by 34 km), and A44 (60 km by 32 km) (Figure 3.21).

Figure 3.21 Iceberg A22A Dimensions in early June 2007 are 49.9 by 23.4 km (credit NASA, Earth observatory[44], 2007 n.p.)

The general calving frequency in the Ross and Ronne Ice Shelves is of several decades. In 2000 the Ross Ice Shelf and the Ronne Ice Shelf released 23,000 km^2 of ice, or around 1.5% of the total area of all ice shelves in Antarctica. For Antarctic, very large icebergs can be expected to be produced several times a decade. According to Young (AAD[45], 2001 p. 25) on the contrary to these natural processes: “there has been a dramatic decrease in the area of relatively small ice shelves fringing the Antarctic Peninsula over several decades”.

As an example: the calving of Larsen ‘A’ from at 65° S in 1995 January, from the northern section of Larsen Ice Shelf[46]. In 2006, in Antarctica, a giant iceberg cracked into pieces due to a huge swell caused by an Alaskan storm (MacAyeal *et al.*, 2006[47]). Part of this iceberg was observed in New Zealand in 2008 (Figure 3.22).

[44]http://commons.wikimedia.org/wiki/File:Iceberg_A22A,_South_Atlantic_Ocean.jpg
[45]http://www.antarctica.gov.au/__data/assets/pdf_file/0014/21182/p24_25_science.pdf
[46]http://www.global-greenhouse-warming.com/Larsen-Ice-Shelf.html
[47]http://www.earth.northwestern.edu/people/emile/PDF/EAO186.pdf

Figure 3.22 Tabular Iceberg New Zealand (credit V Aviation[48], 2008 n.p.)

The combined weight of these icebergs was over 5,000 billion t which corresponds to the global annual water consumption.

These calving phenomena of icebergs have been observed at the same time as the several degrees air temperature warming noted since the 1940s in the Peninsula region. The reduction mass of the ice shelves in Antarctica is accelerated by the melting and refreezing of water. Melt water affect ice shelves structure through crevasses. Figures 3.23 and 3.24 show the edge of an ice shelf, from which tabular icebergs form.

Figure 3.23 Edge of an Ice Shelf (credit Dargaud[41], 1997-2009 n.p.)

Figure 3.24 Ice Shelves and Tabular Iceberg (credit Dargaud, 1997-2009 n.p. [41])

[48] www.newzeal.com/theme/heli/Icebergflight.htm
[48] http://www.gdargaud.net/Antarctica/Icebergs.html

Gladstone *et al*. (2001) estimated that smaller sized icebergs, with a length of 1 km or less, could contribute about 410 Gt/year of freshwater to the Southern Ocean via the Weddell Sea. Utilising less than 2% of the iceberg freshwater in Antarctica could provide a 70 km^3/year supply to Australia, which represents the national yearly water consumption.

3.6 Natural Routes of Icebergs

Icebergs often take quite eccentric paths, which can be two or three times the distance of their straight line movement. In addition to the physical features of icebergs (shape, depth, density) a number of other factors are responsible for the speed and direction of iceberg drift. Among the most important of these factors are the variable pressure of seawater, the intensity and orientation of ocean currents and surface winds, the orientation of the Coriolis force at the sea surface, the viscosity of water, and their state (Chapman, n.d.).

A maritime current is characterised by horizontal motions of water at the ocean's surface. Two forces driving ocean currents are the sun and the rotation of the Earth. According to Bezryadina (2006[49] p.1): “the Sun heats the atmosphere, creating winds which [are] moving the sea surface through friction.” Its influence does not extend much below about 100 m in depth. Bezryadina also explains that:

> [t]he Sun is to alter the density of the ocean surface water directly by changing its temperature and/or its salinity. If water is cooled or becomes saltier through evaporation, it becomes denser. This can result in the water column becoming unstable, setting up density-dependent currents, also known as the thermohaline circulation.

Scientists can use the density structure of the ocean to calculate the pressure field and gradients. The variability of the height of the sea surface changes according to pressure levels. Surface ocean currents maps can be designed (Figure 3.25).

[49] http://physics.ucsc.edu/~sriram/Classical_Mechanics_class_presentations/abstracts_of_student_seminars_CM210.pdf

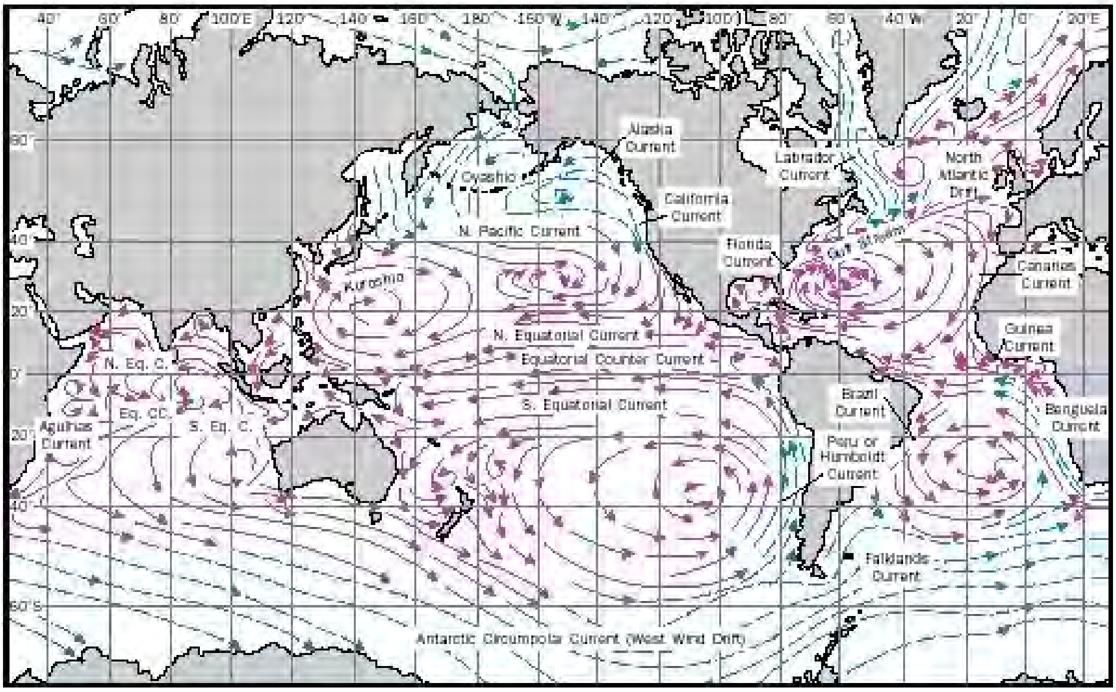


Figure 3.25 Global Surface Current System under Average Conditions for North Hemisphere Winter. Red arrows represent warm currents and blue arrows cold currents (credit Chapman[50], n.d.n.p.)

Compared to surface flows subsurface currents or gyres are low speed currents (Chapman, n.d.; Pidwirny, 2006). They are formed by the seawater density gradients. Five main gyres exist (North Pacific, South Pacific, North Atlantic, South Atlantic and Indian Ocean). In Antarctica, several currents influence the routes that icebergs take in the Southern Ocean.

Perhaps the most critical current to affect iceberg movement is the Antarctic Convergence that links all the oceans of the world together in a clockwise flow around the South Pole (Schmitz, 1996).

Westerly winds blow permanently in the Southern Ocean as there are no land masses; a continuous circum-global current can form (Barker, 2007). The Antarctic Circumpolar Current (ACC) flows eastward around the Antarctic through South Atlantic, Indian and Pacific Oceans (Klinck and Nowlin, 2001). The ACC has depths from 2,000 m to 4,000 m and width up to 2,000 km. The vertically integrated flow of the ACC consists of interactions between the density fields and the bottom topography and is concentrated in the upper 1,000m of the

[50] www.waterencyclopedia.com/Mi.../Ocean-Currents.html

ocean (Hibler and Zhang, 1994 and 1995). The region within which the ACC operates experiences significant water mixing from several ocean basins. The ACC volume flux is 120 Sv (Whitworth, 1983; Peterson, 1988).It increases the transport south of Tasmania where the ACC becomes one of the largest volume currents on the planet with a volume flux of 147 Sv (Knauss, 1996). According to Smith *et al.*, (2001-2008 n.p.) the ACC limits change because of:

> [t]ides (5-10 cm/s), mesoscale eddies (1 cm/s), near-inertial motion (10 cm/s), and large-scale wind stress (25 cm/s) (Sarukhanyan, 1985) … The ACC's boundaries are generally defined by zonal variations in specific water properties of the Southern Ocean (Gordon *et al*., 1977).

Smith *et al.*, (2001-2008) situate the Subtropical Convergence or Subtropical Front (STF), north of the ACC (between 35° S and 45° S). Its average Sea Surface Temperature (SST) decreases from 12°C to between 7 and 8°C. According to Smith *et al.*, (2001-2008[51] n.p.): "[T]he eastward flow of the Subantarctic Front (SAF), found between 48° S and 58° S in the Indian and Pacific Ocean and between 42° S and 48° S in the Atlantic Ocean, defines the ACC's northern boundary".

South of the STF and north of the SAF, the Subantarctic Zone (SAZ) has an average Sea Surface Temperature (SST) of greater than 4°C. Further south, the SAF and the Polar Front (PF) have an average SST of less than 2°C (Smith *et al*., 2001-2008). The bulk of the transport is carried in these middle two fronts. The Antarctic Convergence is located around 200 km south of the Polar Front. According to Smith *et al.* (2001-2008[52] n.p.): "[I]n the Antarctic Convergence, summer SST varies between 3°C to 5°C, while winter SST varies between 1°C to 2°C" (Figure 3.26).

[51] http://oceancurrents.rsmas.miami.edu/southern/antarctic-cp.html
[52] http://oceancurrents.rsmas.miami.edu/southern/antarctic-cp.html

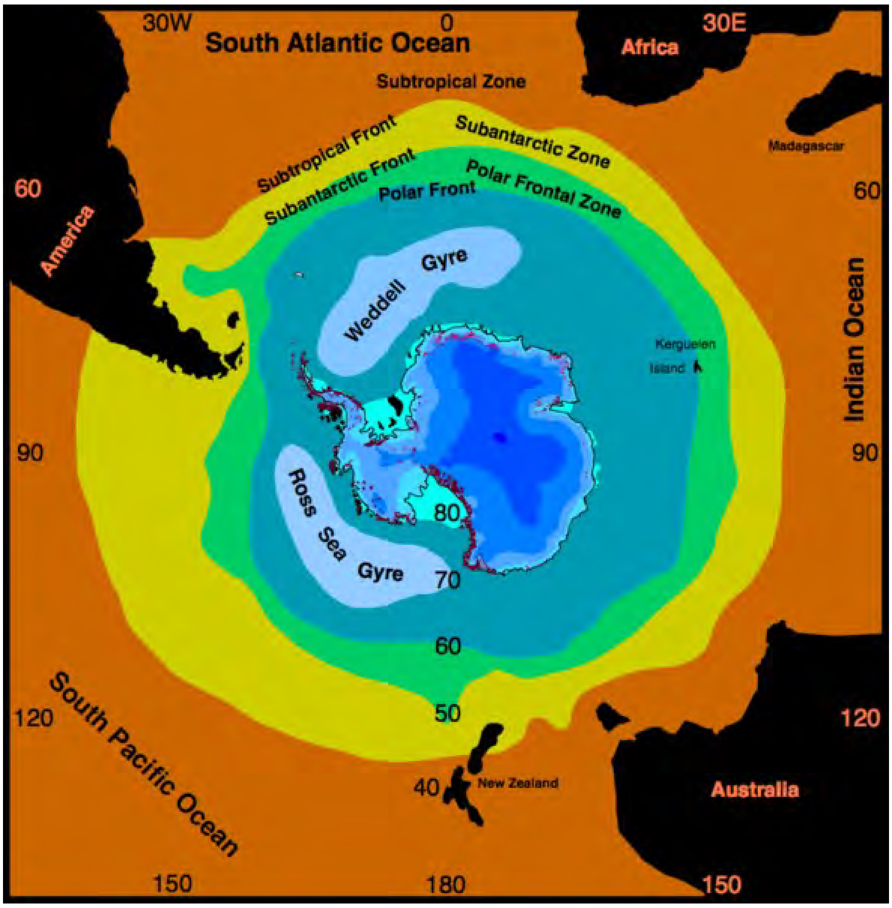


Figure 3.26 Antarctic Frontal Systems (credit Grobe, Alfred Wegener Institute, 2007[53] n.p.)

Further south still is the southern boundary front. The westward flowing Antarctic Polar Current is located pole ward of 65° S, between the southern front and the Antarctic continent (Rintoul *et al.*, 2001[54]). The SST of this region is about -10°C in winter (Deacon, 1984). According to Smith *et al*. (2001-2008[55] n.p.):

> The southern boundary of the ACC is approximately at 65° S in most of the Indian and Pacific Ocean, from 50° E to the dateline; moves northward to 60° S, east of the dateline to 140° W; is near 70° S by 120° W and moves northward to 60° S, east of the Drake Passage.

The surface current is powerful northward, and induced by westerlies.

[53] http://commons.wikimedia.org/wiki/File:Antarctic_frontal-system_hg.png
[54] http://epic.awi.de/Publications/Rin8888b.pdf
[55] http://oceancurrents.rsmas.miami.edu/southern/antarctic-cp.html

According to Smith *et al*. (2001-2008[56] n.p.):

> [Strong pressure] gradients give rise to stronger flows, and the majority of the ACC transport is associated with fronts within the current. Gille (1994) analysed GEOSAT altimeter data and found two well-defined jets in the ACC, at the PF and the SAF, with widths between 35 and 50 km and a dominant meander wavelength of 150 km.

At the southern boundary front, very dense abyssal waters up-well within a few hundred meters of the surface in the Continental Zone (Klinck and Nowlin, 1986 in Smith *et al*., 2001-2008). The southern limit of the ACC could be located further south. According to Orsi *et al*. (1995) and Park (1997) the ACC limit could be assimilated with the Upper Circumpolar Deep Water (T > 1.8°C).

According to Pidwirny (2006 n.p.) the deep currents are made from: "[C]old and dense seawater which comes from the equator, travels eastward joining another deep current created by evaporation occurring between Antarctica and the southern tip of South America".

These deep currents do not directly affect iceberg routes. Figure 3.27 shows the different currents involved in the Southern Ocean.

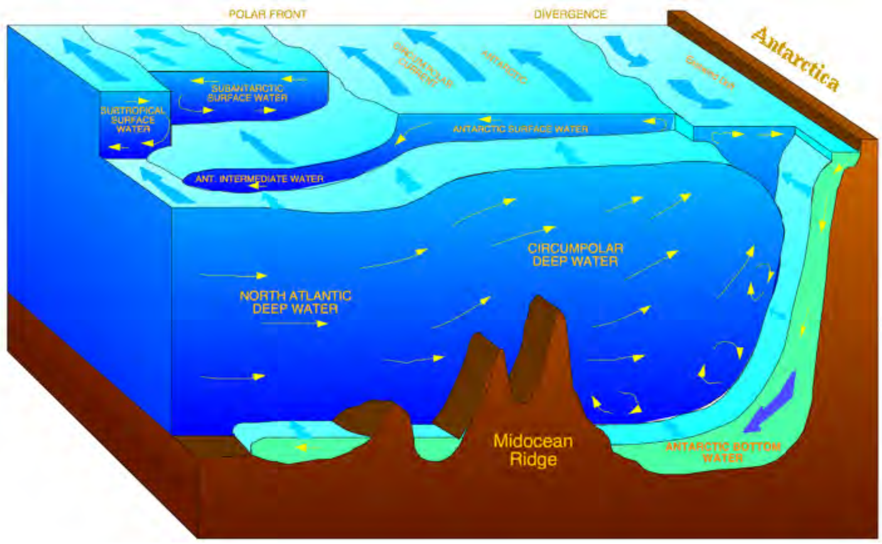


Figure 3.27 Patterns of Different Currents Involved in the Southern Ocean (credit Grobe, Alfred Wegener Institute[57] 2000 n.p.)

[56] http://oceancurrents.rsmas.miami.edu/southern/antarctic-cp.html

Currents of the Southern Ocean have persistent spatial and seasonal patterns even though these patterns can change subject to weather conditions, which are related to hydrological and wind cycle variability. The ACC's eastward flow is relatively slow in regions between the fronts: less than 20 cm/s at the STF, 40 cm/s in the SAF and PF (Hoffmann, 1985) and 15 cm/s in the PFZ (Zambianchi *et al*., 1999). According to Smith *et al*. (2001-2008 n.p.):

> [The ACC's] eastward flow is driven by strong westerly winds (average wind speed between 40° S and 60° S is 15 to 24 knots with strongest winds typically between 45° S and 55° S).Surface winds blow towards areas of low pressure and upper level winds would blow away from the corresponding area of high air pressure above.

A polar pressure cell is best developed over Antarctica because of a relatively uniform ice covered continent. Mid latitude circulation is driven by interactions between polar and subtropical air. Near the fronts, powerful eastward jets flow (Klinck and Nowlin, 2001).The Coriolis force is created by the rotation of the Earth and the friction of the sea with the Earth at the seafloor. The eastward linear velocity is strongest at the equator and smallest at the poles. When it moves north water moves eastward to keep the same momentum according to its mass and velocity. Consequently the Coriolis force increases while it moves from the equator. The surface of the ocean has then a limit of horizontal pressure gradient. According to Chapman[58] (n.d. n.p.):

> The combination of the Coriolis force and the horizontal pressure gradient produces a current that flows at right angles to the pressure gradient; when the two forces are equal the current is geostrophic. All major ocean current systems can essentially be considered geostrophic.

The atmosphere has a complex impact on the calving, drifting, and climatic environment within which icebergs are formed and degrade. The stress state of iceberg has been discussed by Diemand (1986). The circumpolar tracking of icebergs provided indication of the general drift directions of icebergs (Swithinbank *et al*., 1977; Budd, 1980; Stuart *et al*., 2007; Scambos, 2008). Schodlok *et al*. (2005a and 2005b) also studied iceberg paths in Antarctica. Fifty-nine icebergs were tagged with buoys in the Weddell Sea by AWI in 1996 (Schodlok, 2004; Schodlok *et al*., 2005a and 2005b). Figure 3.27 shows the drift path of the tabular iceberg A-38 from the Ronne Ice Shelf to the Weddell Sea, the Scotia Sea and South

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[57] http://commons.wikimedia.org/wiki/File:Antarctic_bottom_water_hg.png
[58] http://www.waterencyclopedia.com/Mi-Oc/Ocean-Currents.html

Georgia, from October 1998 to March 2004 (Jansen, Sandhager and Rack, 2005; Jansen Schodlock and Rack, 2007).

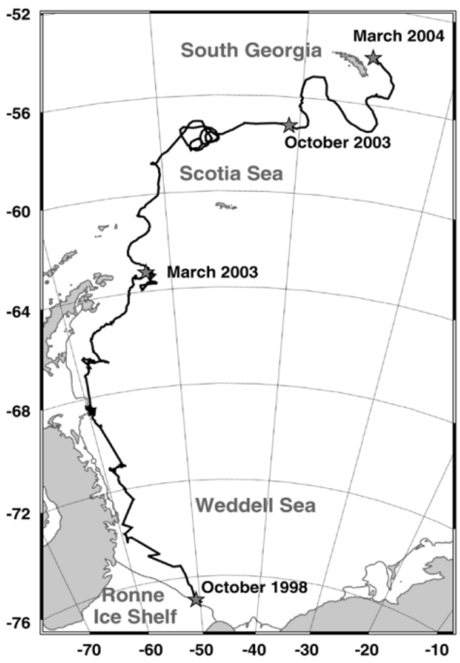

Figure 3.28 Drift Path of the Tabular Iceberg A-38B (credit Jansen, 2008 QuikScat data from the Antarctic Iceberg Data Base[59] BYU p. 86)

The GPS position of the selected tagged icebergs was transmitted daily over a two year research period. For buoy deployment, icebergs with edges smaller than 2 km long are preferred, however, some larger icebergs (among them A-43B, 40 km by 7 km) were also tagged. According to Schodlok *et al*. (2005[60] p.1) the iceberg: “A-43B was grounded southwest of South Georgia for about a year, before it started to break up and move north again in early 2004. Part of the iceberg, containing the buoy, broke off about half a year earlier”.

The buoy survived the calving and continued to transmit for six more months. The majority of icebergs buoy systems transmits between one and two years. The study drew several conclusions, including:

[59] epic.awi.de/Publications/Jan2009d.pdf
[60] http://folk.uib.no/ngfso/FRISP/Rep16/schodlok.pdf

- the existence of a coastal current indicated the dependence of northward movement towards the inner Weddell Sea. Icebergs size was small and varies with season;
- the Weddell Scotia Confluence featured different iceberg sea-ice behaviour, with large icebergs moving north into the Scotia Sea, before being trapped in the Convergence front. The eastward drift followed the Weddell Gyre toward the east (Thompson *et al.*, 2009);
- the Eastern Weddell Gyre part indicated a recirculation around the continent.

Iceberg drift determines where fresh water from the Antarctic continent is supplied to the world's oceans. Iceberg drift speed is influenced by iceberg size and shape, ocean currents, sea temperature, and the force of waves and winds. Icebergs drift more when the atmospheric pressure is low and the currents are stronger. Once released, icebergs are carried northward and westward with an average drift speed for tabular icebergs of 1 m/s, 3 km/day and up to 8 km/day in the easterly wind and currents around the continent (Schodlock, 2005). Icebergs eventually reach the Convergence or the Polar Front of the Antarctic Circumpolar where they drift and melt (Figure 3.29).

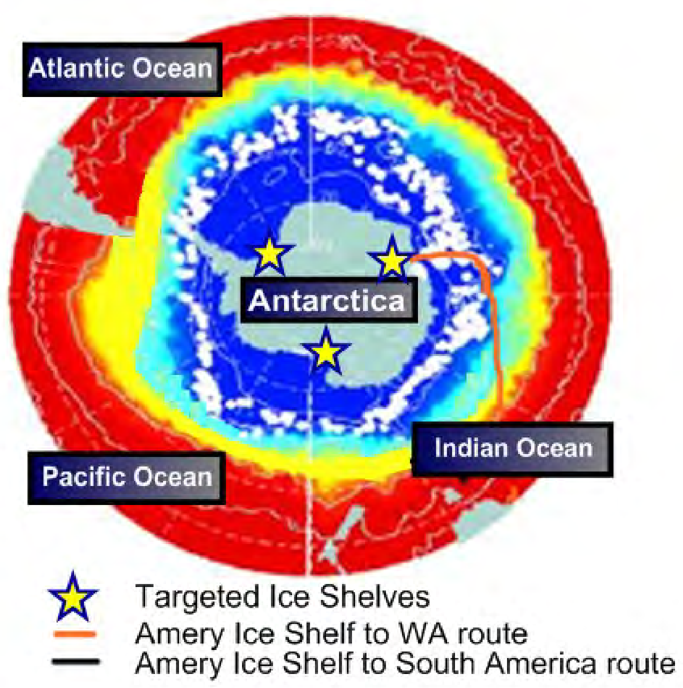

Figure 3.29 Iceberg Dispersion around Antarctica (see white spots) (credit adapted from Vendée Globe sailing race map CLS[61] 2008 n.p.)

[61]http://www.solarnavigator.net/vendee_globe_yacht_race_2008.htm

Tabular icebergs tracked by satellites have shown maximum long-term drift rates of up to 4 m/s or 12 km/day (Marko *et al*., 1983). At the northern limit of the circumpolar waters, icebergs meet warmer water and they rapidly melt. The furthest north an iceberg has been sighted is at 26°30 S in the South Atlantic, almost in the tropics (Marko *et al*., 1983). This gives indications about the potential sites where icebergs could be harvested for freshwater utilisation.

3.7 Melting and Life Expectancy of Icebergs

In Antarctica, the temperature of icebergs is in the range of $-15^{o}C$ to $-20^{o}C$. During the melting process icebergs often calve and fracture; it creates ‘trails’ or ‘halos’ of growlers. The action of sea waves icebergs is generally the main source of iceberg melting and means that melt occur more often at the waterline. The main sources of decay of icebergs are the water temperature and storms. Erosion is maximal when the iceberg is affected by both mechanical erosion and thermal effects of air and water. Icebergs can melt into saddle, teeth or bipeaked shapes because of unequal erosions between their axes. The parts most affected by erosion rise which creates motion. During the melting process the iceberg shape will be modified as seen in Figure 3.30.

Figure 3.30 Field Observation of Iceberg Deterioration (credit Veitch *et al.*[62], 2001 p. 1)

For each shape the iceberg will find a new physical stability condition passing through a transitory equilibrium state. In warm waters, icebergs often become very unstable. The indentation at the waterline stimulates calving of the suspended and underwater parts of icebergs. However, melt and break-up rates vary with water state and temperature. Melting

[62]ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Deterioration_01.pdf

conditions are accelerated or decelerated by daily and seasonal oceanographic and atmospheric variations and also by the route followed by the iceberg (Jansen, 2009). Ocean conditions usually have a strong impact on the melting process (Veitch and Daley, 2000). The waterline is stressed by sea waves and by warm water currents and consequently compression and dilatation of ice take place. When the air temperature is warmer than the sea temperature (by more than 2°C) the emerged parts of the iceberg will melt faster (Jansen, 2009). When the water temperature is warmer than the air temperatures (such as in the case of the Gulf Stream's 'cold wall'), the melting rates are faster within the submerged area. During the iceberg drift, the wind and the sea state (waves, sea ice) act as driving forces (Smith and Donaldson, 1987; Smith, 1992 and 1993). These driving forces can be implemented in a numerical model, and can be related to iceberg length reduction (Gladstone *et al*., 2001; Schodlock, 2005[63]). The influence of solar radiation (White *et al.*, 1980) on the melting of icebergs is neglected because it is very small, less than 0.2 MJ/m^2 (Veitch *et al.*, 2001).

Numerical and experimental physical models of iceberg deterioration have been proposed in the last ten years (Martin *et al.*, 1977; Veitch and Daley, 2000; Liang *et al*., 2001; Moores *et al*., 2001). These models have successfully integrated a number of critical factors responsible for iceberg deterioration, such as iceberg orientation, floatation, stability and mass evolution due to continuous melting and morphological changes. The main focus was put on studies related to wave accelerated melting which have a determinant influence on calving fragmentation. At the waterline of an iceberg, wave erosion produces protruding underwater rams and cantilevered shelves above water. Veitch et al. (2001[64] p. 4) noted:

> The buoyancy forces on the former and the gravity forces on the latter frequently lead to large scale fractures of the iceberg. Removal of mass by a fracture changes the stability of the iceberg and exposes cold interior surfaces to warmer water, leading to further stresses and fractures. The resulting fragmentation reduces the mass of an iceberg at a much higher rate than wave erosion alone would achieve.

Figure 3.31 illustrates the fragmentation of an iceberg as recorded by a video compared with the results from a corresponding simulation. The sequence of pictures in Figures 3.32 to 3.34 shows the wave erosion on an iceberg during 47 ¼ hours, from May 27 to May 29, 2001. The iceberg was observed in the village of Little Harbour - Canada.

[63] http://folk.uib.no/ngfso/FRISP/Rep16/schodlok.pdf
[64] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Deterioration_01.pdf

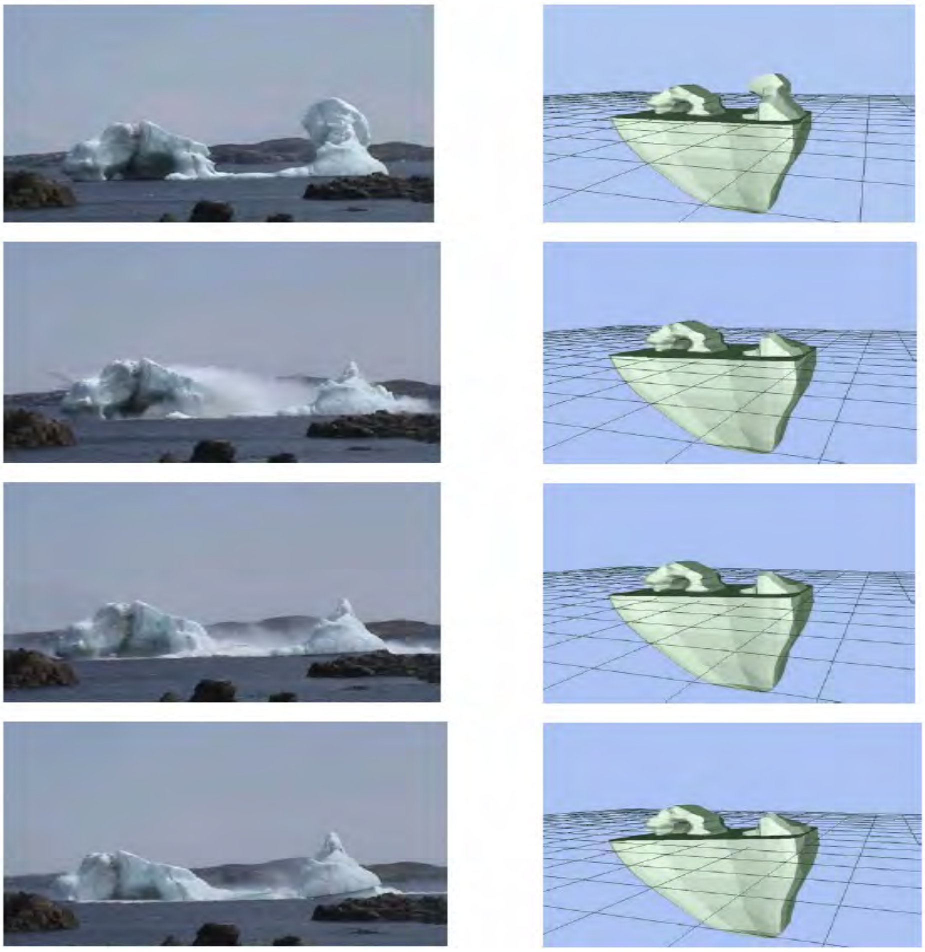

Figure 3.31 Fragmentation of an Iceberg (credit Veitch *et al*., 2001 p. 12)

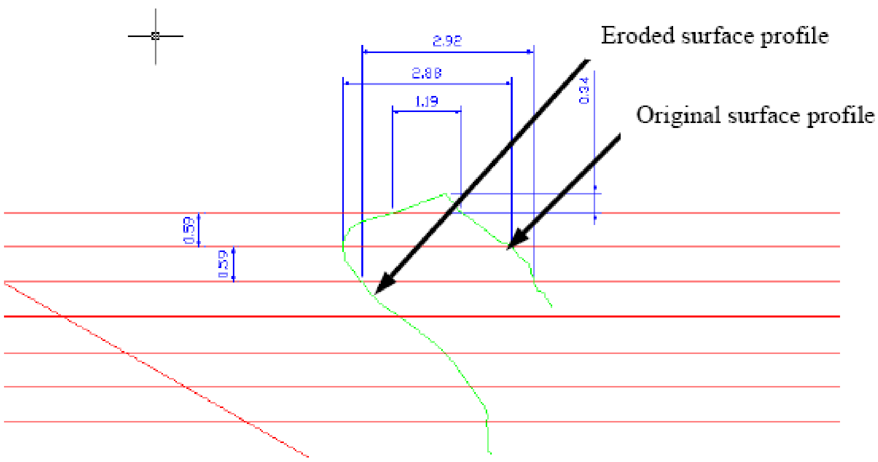

Figure 3.32 Outline Profile of the Iceberg Showing Wave Erosion (credit Veitch *et al*., 2001 p. 14) in green the erosion compared to the original profile

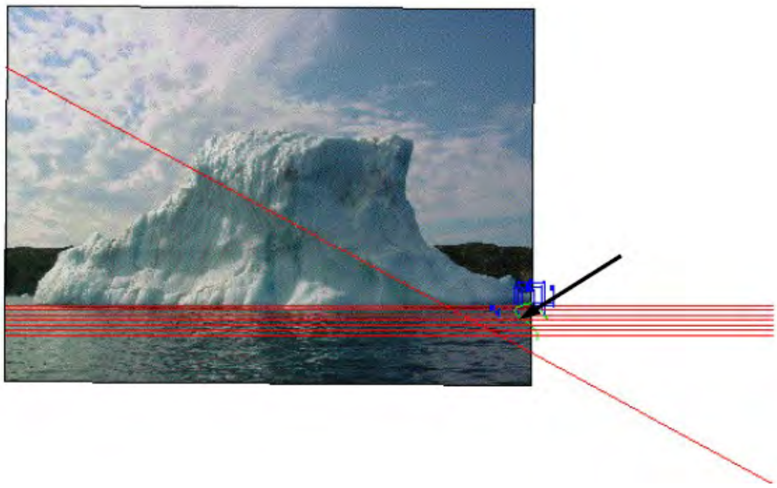

Figure 3.33 Wave Erosion on an Iceberg during 47 ¼ hours, from May 27 to May 29, 2001. Little Harbour, Canada. The Arrow Surface Indicates Waves Erosion (credit Veitch *et al*., 2001 p. 15)

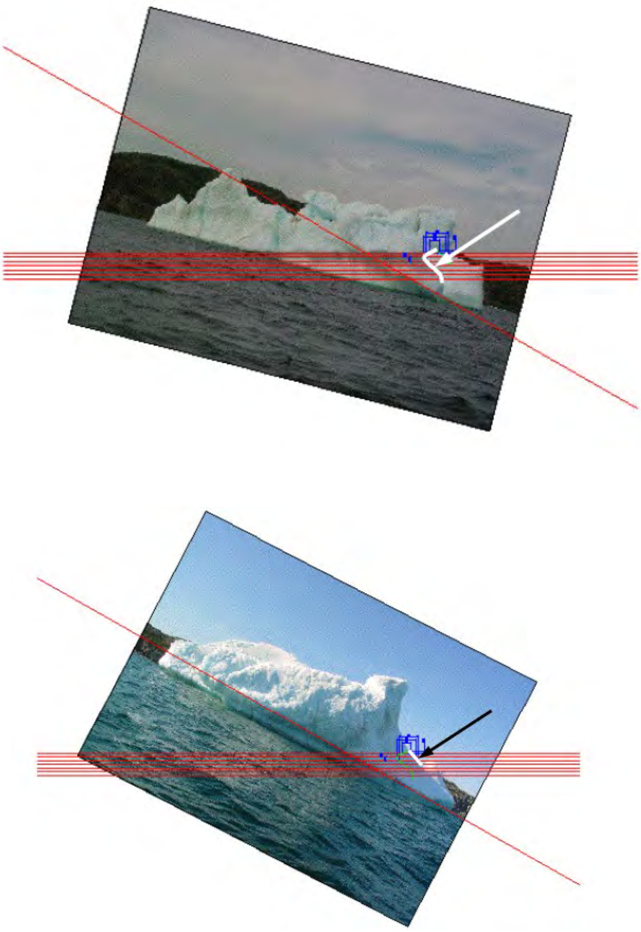

Figure 3.34 The Surface Eventually Gets Eroded by Waves as Indicated by the Arrow (credit Veitch *et al*., 2001 p. 15)

The orientations changes of the iceberg, its profiles and waterlines are recorded and show the eroded surface lines. According to Bruneau (2010[65]) “a large berg may take 90 days to fully deteriorate in water temperatures around 0^{o}C, whereas the same berg may only last 11 days in 10^{o}C water”. A 120 m long large iceberg (for Arctic icebergs) melted in 36 hours in 27^{o}C water (Bruneau, 2002).

In the Antarctic, most tabular icebergs take several seasons to deteriorate, and some are grounded for years in shallow bays. The average life of the other types of large icebergs is around six years (Hellmer, 2004). Tabular icebergs from ice shelves are bigger and stronger in the beginning, and therefore have a much longer life (up to 11 years) than smaller density icebergs. Iceberg drift and decay depend on whether icebergs are driven completely, partially or stay close to their original location (Schodlok *et al*., 2005b). Freshwater flux from icebergs depends on iceberg decayed time. Net precipitation input can compensate icebergs freshwater flux output (Schodlok *et al*., 2005b). These elements are important for the understanding of the harvesting techniques of icebergs and the study of their potential impacts.

3.8 Conclusion

In this chapter the properties of icebergs have been analysed. Specific characteristics of icebergs, including their mechanical properties, underwater volume, dielectric and optical properties provide important information which would be necessary to develop an iceberg transportation system. For example, variables such as the suitable volumes of ice that could be used, the types of icebergs which are the most stable, the time for icebergs harvesting, the ideal locations to source icebergs, the techniques to operate icebergs, the environmental properties which can be used and the environment characteristics which have to be protected. In Antarctica, the annual precipitation would correspond to 5 mm of sea level rise. This accumulation is compensated partially by ice discharge into floating ice shelves that very often break up to form icebergs (Church et al., 2001[66]). The size of the global iceberg resource is estimated at 3,000 billion tonnes/year and is equivalent to more than half of the world’s water consumption. In Antarctica, the harvestable tabular iceberg resource is about 200,000 icebergs/year. Using 1% of the resource would not overtake the regeneration of the resource (up to 10 km^3/year, 0.03 km^3/day). A theoretical global ice daily volume of up to 3

[65] http://www.icebergfinder.com/iceberg-guide/iceberg-faq.aspx,http://www.caperace.com/stories/where-do-icebergs-really-come-from/

[66] www.grida.no/climate/ipcc_tar/wg1/pdf/TAR-11.pdf

km^3 (up to 1,200 km^3/year) would be available providing that environmental impacts of their harvesting could be minor.

According to Church et al. (2001 p. 650):

> Changes in ice discharge generally involve response times of the order of 10^2 to 10^4 years, the time scales are determined by isostasy, the ratio of ice thickness to yearly mass turnover process [up to 4,500 km^3], affecting the velocity the physical and the thermal processes at the sea bed.

Melting produces iceberg instability. During the melting process icebergs often calve and fracture into many small pieces. The action of sea waves icebergs is generally the main source of iceberg melting and means that melt occur more often at the waterline. Their melting rates vary according to their environment. Antarctic tabular icebergs are the most appropriate for a project of freshwater supply because of their properties. The temperatures of tabular icebergs are between -15°C and -20°C. Between two to five years are needed for total iceberg disintegration of a tabular iceberg. Therefore tabular icebergs, have the required characteristics to be successfully selected for transportation. They have the most reliable physical stability, which minimises risks associated with harvesting. They offer large volumes and could therefore be considered as semi fossil water supply resources as the ratio between the scale of the resource and the times of regeneration is small. Icebergs are natural ice outputs into the sea. The natural routes of iceberg movement are favourable for a maritime transportation system. Locations with a reasonable accessibility to tabular icebergs could take advantage of the transportation of icebergs as a solution to local freshwater shortages. This is a key point of the thesis. New operating techniques would still need to be designed to stabilise icebergs for transportation purposes. And the environmental impacts of their use would require a more detailed investigation on the characteristics of the environments of iceberg which will be undertaken in the next chapter.

Chapter 4 The Environments of Icebergs

Figure 4.0 Icebergs, Baffin Island (credit Walk, 1997; 2001[1] n.p.)

1 http://commons.wikimedia.org/wiki/File:Iceberg_10_2001_07_23.jpg,
http://commons.wikimedia.org/wiki/File:Iceberg_7_2001_07_23.jpg?uselang=de
http://commons.wikimedia.org/wiki/File:Iceberg_8_2001_07_23.jpg
http://commons.wikimedia.org/wiki/File:Iceberg_5_1997_08_07.jpg?uselang=de

Chapter 4 The Environments of Icebergs

In this chapter the climatic, ecological, geophysical and environmental characteristics of icebergs and their impact on polar environments will be described. The lifecycle of icebergs and their regional and local impacts will be analysed with comments on their effects on flora and fauna. The optimal locations in the Antarctic Australian Territories (AAT) from which to source icebergs for transportation and the quantities of ice that can be sustainably harvested will also be examined. These characteristics will be used to elaborate assumptions to support the design of a model, described in Chapter 7, to assess the feasibility of different iceberg transportation techniques and facilitate an assessment of the impacts of iceberg transportation on the atmosphere, the hydrosphere and the ecosphere in the current climate context.

4.1 Antarctic Climate

For climate studies, information about atmospheric and geophysical parameters of the land and ocean surface are provided by meteorological data delivered by the United States NOAA - National Ocean and Atmospheric Administration - operational polar orbiting satellites [2]. These meteorological satellites are in geostationary orbit and have been operational for two decades (CGMS[3]). Susskind *et al.* (1997) described the characteristics of the data set and the method of analysis. They refer to surface temperature (surface air and Earth's radiative ocean temperatures), precipitation and winds. To understand how Antarctica responds to climate change and its consequences for iceberg production and lifecycle, in this section I will describe the Antarctic climate with reference to the air and land (air temperature, precipitation and winds) and to the ocean. Benthic temperatures will be discussed because of the relationship between iceberg drift and currents.

4.1.1 Surface Air Temperatures

In Antarctica, temperature decreases with elevation, from the sea level to the high mountains (4,000 m altitude). The ocean's heat is conducted through the icepack. The centre of the

[2] TIROS - Television Infrared Operational Satellite,
TOVS - Operational Vertical Sounder
MSU - Sounding Microwave Unit
[3] Coordination Group for Meteorological Satellites
http://www.wmo.int/pages/prog/sat/CGMS/Directoryofapplications/en/cover.htm

Antarctic continent is cold and dry. Heavy snowfalls are frequent on the coastal zone of the continent.

Surface air temperatures (Figure 4.1) range between -80°C and -90°C inside the continent in winter, to between 5°C and 15°C in the margin in summer (Antarctic Connection[4]).

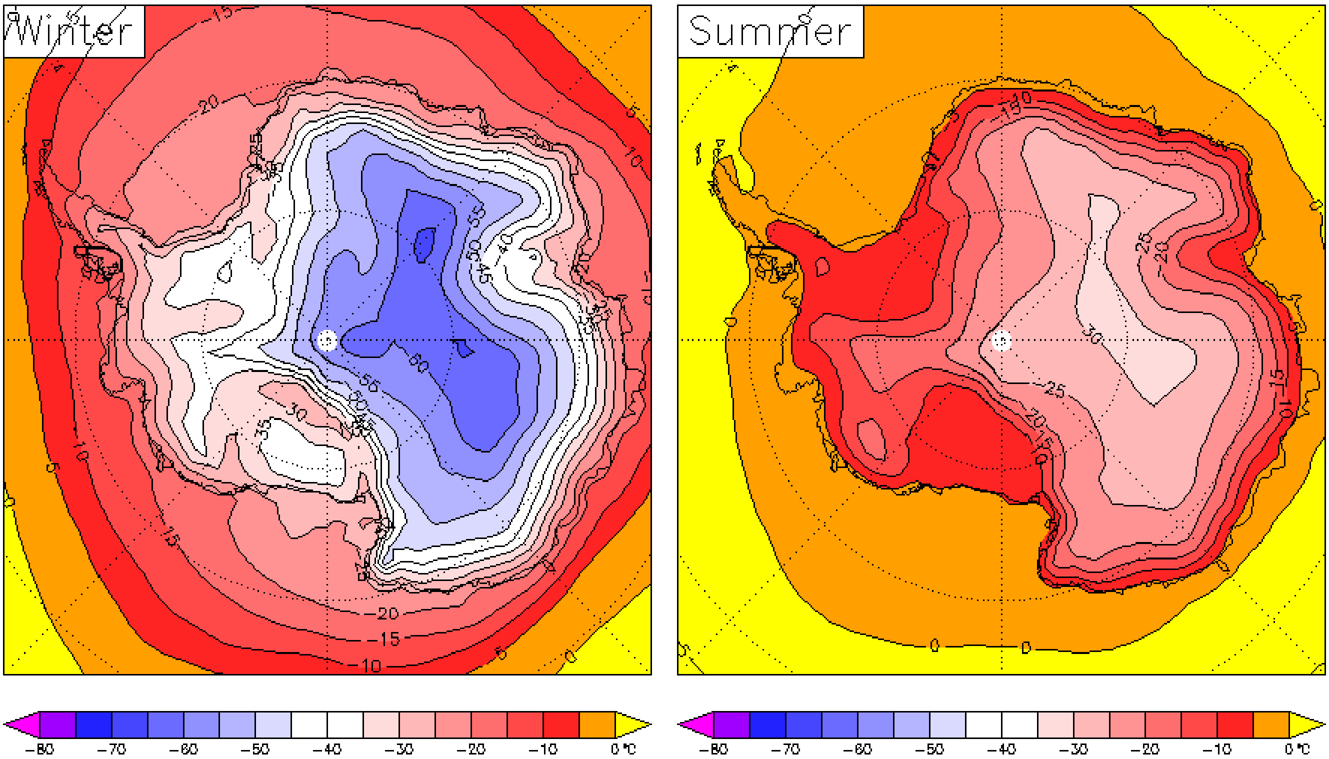

Figure 4.1 Antarctic Surface Temperatures from Data between 1979 and 2001 in Winter (June, July, August) and Summer Months (December, January, February) (credit Connoley[5], n.p.)

High plateau temperature is colder than coastal zones because of its elevation and reduced solar radiation (Vaughan *et al.*, 1999). Around the coasts, katabatic winds can blow at high forces, up to 20 m/s whereas in the centre of the continent, wind speeds are more moderate from 5 to 10 m/s (Liu, 1997).

4.1.2 Precipitation

Figure 4.2 shows the average annual precipitation in Antarctica.

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[4] http://www.antarcticconnection.com/antarctic/weather/index.shtml
[5] http://en.wikipedia.org/wiki/File:Antarctic_surface_temperature.png

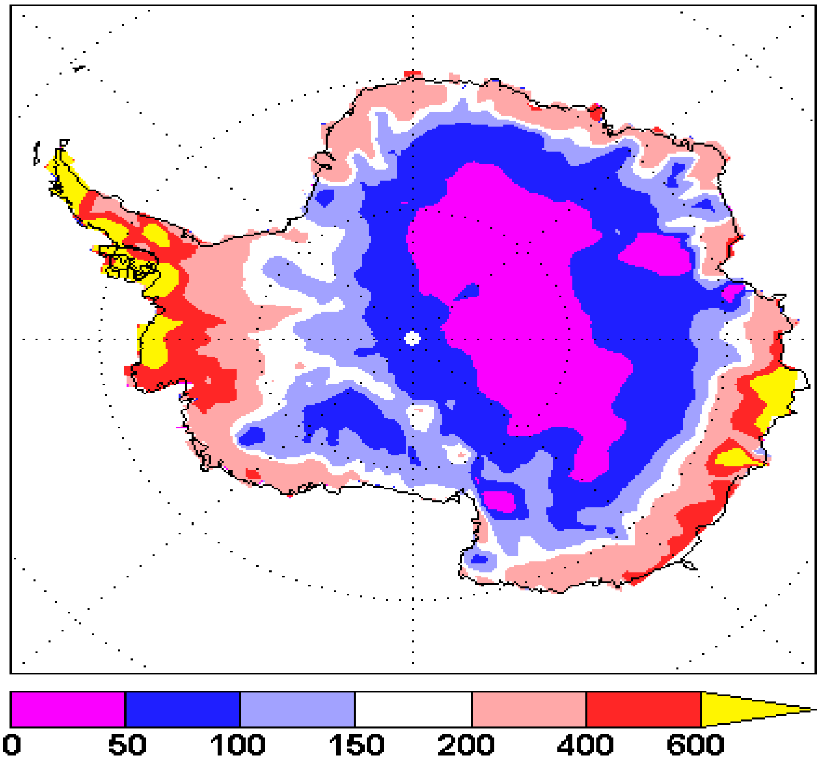


Figure 4.2 Average Annual Precipitations (liquid equivalent, mm/year) in Antarctica (credit Connolley[6], 2009 n.p.)

This continent receives characteristically 166 mm/year. Precipitation ranges between 600 mm/year in the Antarctic Peninsula, and 50 mm/year, similar to a desert, in West Antarctica. The air humidity is very low as a result of low temperatures. Little evaporation over hundreds of thousands of years has generated an enormous ice sheet thickness. Along the coast there is more precipitation than in the interior of the continent. Precipitation occurs in the form of heavy snowfalls from cyclonic storms, which transport moisture from the ocean. Snowfalls of up to 70 cm/day have been reported (King and Turner, 1997; Ward, 2001[7]).

4.1.3 Winds

Antarctica is characterised by very strong katabatic winds, which are produced by differences in air mass density between the polar plateau and ocean and by air pressure and temperature gradients, as can be seen from Figure 4.3.

[6] http://en.wikipedia.org/wiki/File:File-Dgv-surfbal-1.gif
[7] http://www.coolantarctica.com/Antarctica%20fact%20file/antarctica%20environment/whats%20it%20like%20in%20Antarctica.htm

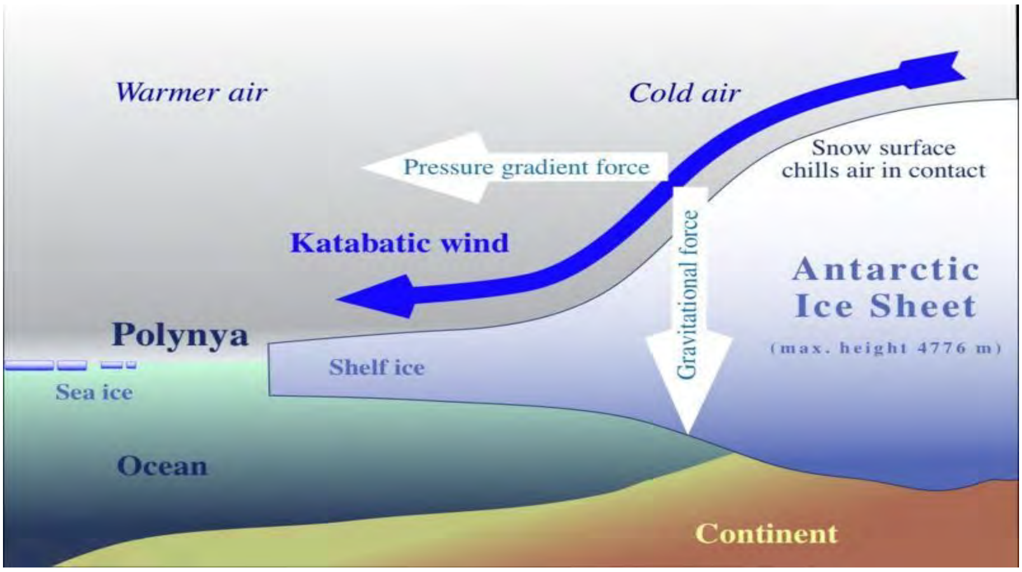
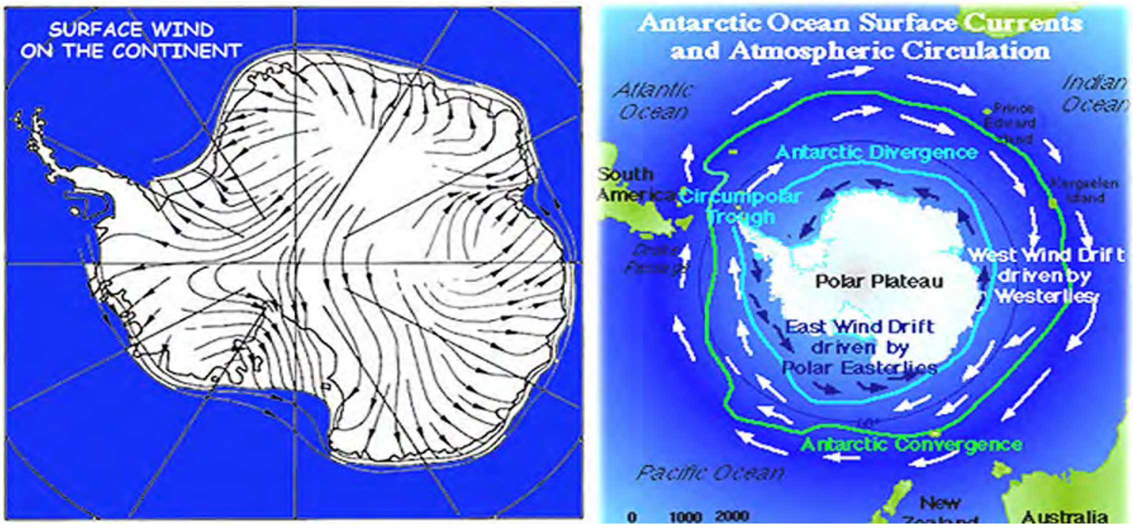


Figure 4.3 The Formation of the Katabatic Wind in Antarctica (credit Grobe and Wagner[8] 2010 n.p.)

Parts of Antarctica are the windiest places on Earth, where average katabatic velocity is 160 km/hour. The highest katabatic speed, 327 km/h, was record in July 1972 at Dumont d'Urville Station (Schneider, 2006[9]). The wind patterns are represented in Figure 4.4a. In the Antarctic Divergence east winds are dominant. In the Convergence westerlies are dominant. Both of these winds turn counter clockwise because of Earth rotation effects (Figure 4.4b).



a. b.

Figure 4.4 Winds Patterns in Antarctica a. and Antarctic Ocean Currents b. (credit [10] 2010 n.p.)

[8] http://onramp.nsdl.org/eserv/onramp:16016/web_katabatic_winds.jpg
[9] http://antarctica.kulgun.net/Weather/
[10] http://www.shorstmeyer.com/msj/geo130/antarctica/winds_antarctic.jpg

The winds have an important impact in the lifecycle of icebergs as was demonstrated by studies undertaken by the University of Chicago. Over a period of eight years (2000-2008) the Department of Geophysical Sciences carried out a research program to study five icebergs (B15A, B15J, B15K, C16, C25) originally from the Drygalski Ice Tongue and one new iceberg, from the Ross Ice Shelf (SCAR, 2008[11]). Figure 4.5 shows the break up of the iceberg B15A, the greatest-ever observed tabular iceberg, on 27 October, 2005. In October 2005 in this zone, the maximum wind speed was 72 km/h. During break up, wind velocity was very low, less than 5 m/s (20 km/h).

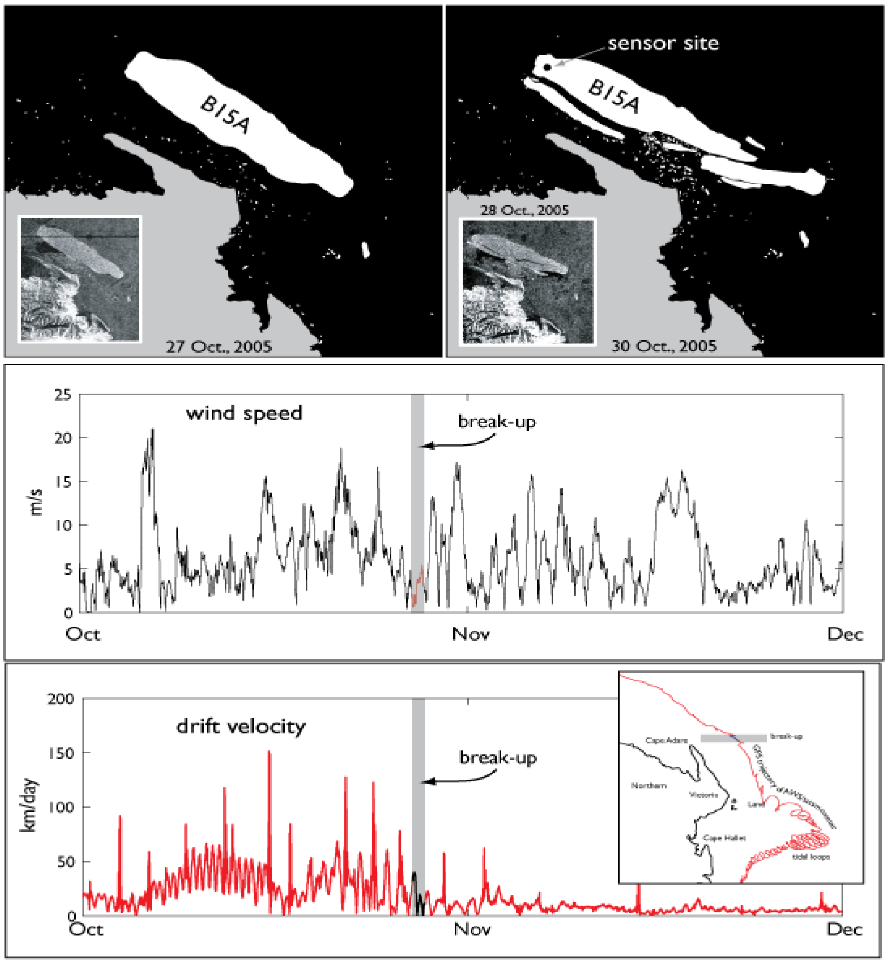


Figure 4.5 Iceberg B 15A Break up on 27 October 2005; drifted until 30 October when, because of winds and sea swell generated by a storm in Alaska 7 days earlier, broke into several parts 30 October 2005 (credit 2010[12] n.p.)

[11] http://geosci.uchicago.edu/i/MosaicB.png
[12] http://geosci.uchicago.edu/i/MosaicB.png

4.1.4 Benthic Temperature

The benthic environment has a major influence on icebergs lifecycle and is characterised by low stable temperatures. The benthic environment is influenced seabed temperatures of the Southern Ocean. Clarke *et al.* (2009 p. 1[13]) noted that: “as a result of flooding of the shelf by Circumpolar Deep Water from the Antarctic Circumpolar Current” the western Antarctic Peninsula shelf is significantly warmer than shelves around continental Antarctica (Figure 4.4b). The greatest seasonal variations in temperature are found in surface waters and shallow sub littoral zones, particularly in the Weddell Sea, Ross Sea, and Prydz Bay where the coldest shelf seabed temperatures have been observed, and are due to seasonal convection and sea ice formation. Near the sea bed at 10 m depth, annual temperatures range from -1.9°C to +0.4°C. Deep areas on the continental shelf at higher latitudes show even smaller variations. Water temperatures are constantly around 3°C and 7ºC in the Antarctic Convergence Zone between 50° S - 60° S (Reddy, 2001). Water oxygen saturation, salinity (34psu) and density (1,026 kg/m^3) are generally stable in the Antarctic Convergence Zone. In zones located near melting icebergs the salinity may be considerably reduced.

Cold and dry climatic conditions in Antarctica and long seasons of continuous darkness and sunlight create characteristic environments. Incident light levels vary with latitude and season. There are seasonal and daily fluctuations in the availability of food and light intensity (Park *et al.*, 1999; Ferreyra *et al.*, 2004[14]). Light penetration is affected by the thickness of ice, the snow cover in winter and the turbidity of the water column in summer. Highest light penetration occurs in spring between the break out of winter fast ice and the onset of the phytoplankton bloom (Schwarz and Schodlok, 2008[15]; Vernet *et al.*, 2009[16]).

Icebergs lifecycle have an impact on the local and regional ecosystem in Antarctica. Some key aspects of flora and fauna in Antarctica, relevant for my project on icebergs transportation, will now be discussed.

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[13] http://www.agu.org/pubs/covers/ASGM112095X.pdf
[14] http://vertigo.revues.org/3172
[15] http://precedings.nature.com/documents/1706/version/1/files/npre20081706-1.pdf
[16] http://polarphytoplankton.ucsd.edu/docs/publications/papers/Vernet_MS_%20Icebergs_Subm042710.pdf

4.2 Ecosystems in Antarctica

The Southern Ocean, including the sea ice zone around Antarctica, supports a wide diversity of life forms (Doran *et al.*, 2002). Antarctica was separated from Australia in the Cretaceous or early Cenozoic era, 40-65 million years ago. Antarctica is separated from the nearest mass land by 900 km (Targett, 1981). Climatic and biotic factors determine the distribution of plant and fauna life in Antarctica. According to the BAS (British Antarctic Institute, 2007 n.p.[17]):

> The majority of the Antarctic continent is covered by permanent ice and snow, leaving less than 1% available for colonisation by plants… Most of this ice and snow-free land is found along the Antarctic Peninsula, its associated islands and in coastal regions around the edge of the rest of the Antarctic continent … Even in the most inhospitable ice-free habitats, such as inland mountains and nunataks, life can still be found".

Around 80% of life in the Antarctic occurs on the West Antarctic Peninsula (Diersen, 2002). Ice movements and changes in sea ice extent are the most important elements for the plant and fauna life in Antarctica. Considering that my thesis aims to evaluate the impact of iceberg transportation on the living conditions of the ecosystems in the Antarctic, in the Appendix 2 I will study Antarctica flora and fauna and the influence of the life cycle of icebergs on the Antarctic ecosystem.

4.3 Lifecycle of Icebergs and the Antarctic Ecosystems

The lifecycle of an iceberg is composed of four phases. The iceberg is laid down as ice in a glacier, is born or calved from the glacier, is drifted in ocean by maritime currents and is melted in the sea water. Icebergs can disturb the ecosystem of the ocean and the margin of the continent such as:

- the environment and the ecosystem of the ocean, because of drifting, melting, scouring the ground, deposition of sediments (minerals ferruginous from original rock, recent volcanic deposits), introduction of carbon and nutrients (as sponge spicules), disturbing the transmitted day light, hiding light and cooling sea water, modifying the temperature and the

[17] http://www.antarctica.ac.uk/about_antarctica/wildlife/plants/index.php

salinity of sea water. Areas of the benthos disturbed in this way take years to re-establish. Icebergs of all sizes can, therefore, disturb the benthic zone;

- the land and the margin of the continent, by mechanical effect during iceberg formation, drifting and melting and the precipitation and temperature variation due to drifting and to melting.

In the next sections I will examine the lifecycle of an iceberg in relation to the Antarctic ecosystem. The focus will be on tabular icebergs which are of main interest for my thesis.

4.3.1 Icebergs as Ice

As we have seen previously, the dynamics of ice sheets is based on the displacement of glaciers, which flow under gravitationally induced stresses. The weight of ice causes glaciers to spread and thin as a function of surface and basal conditions, strain rate and applied stress (Rood, 2007). The geophysical environment of glaciers is different in East Antarctica from that of West Antarctica (Figure 4.6). The glacier flow rate in East Antarctica is about 0.25 km/year while in West Antarctica it is about 1 to 1.5 km/year (Bindschadler *et al.*, 2003).

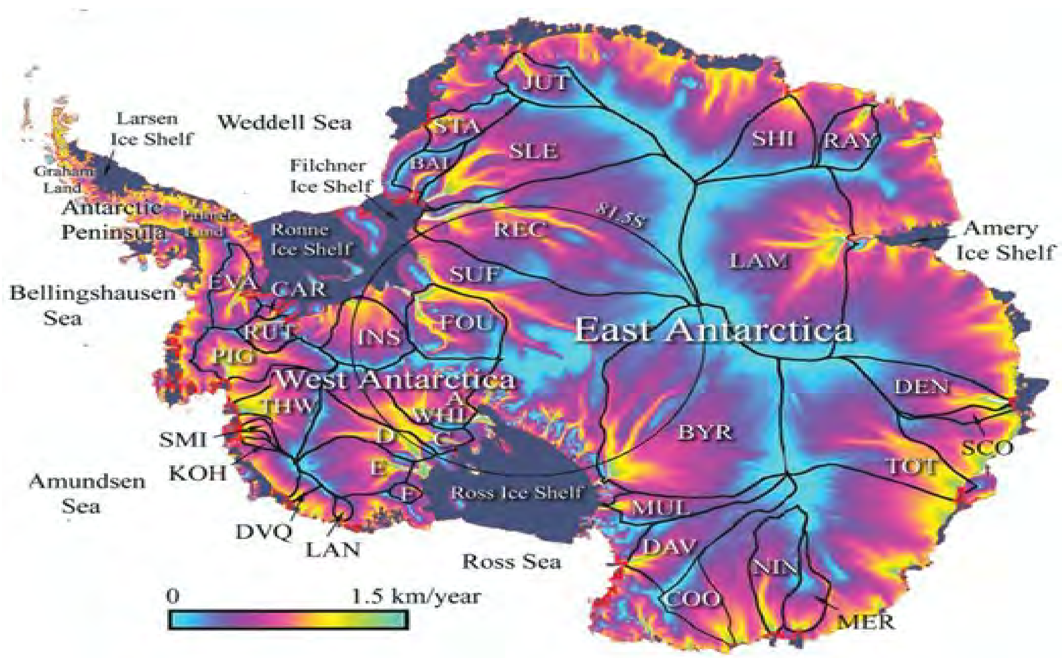

Figure 4.6 Glaciers Flow Rate in Antarctica (credit Bindschadler[18], 2010 n.p.)

[18] http://www.ipy.org/index.php?/ipy/detail/asaid

Over recent decades, Antarctica, as well as Greenland and the North Pole region, have experienced important transformation in response to climate change that can be estimated in mass balance. Vaughan *et al.*, (2003 p. 243) and IPCC (2007) reported that "large regional atmospheric warming" and decreasing winter sea ice may cause increasing temperature. According to Shepherd *et al.*, (2004[19]) basal melt rate occurs at a rate of about 10 m/year/degree Celsius in water temperature under an ice shelf. This could lead to ice shelf thinning and structural instability. In the interior of the Antarctic continent a cooling in temperature has been reported by Hansen (2007). The South Pole Region cools because of increasing precipitation due to ocean temperature increasing, and also because of the presence of the ozone hole (Thompson and Solomon, 2002). The western Antarctic coasts have experienced one of the most rapid average temperature increases since 40 years. Hansen (2007[20] p.3) noted that: “[T]he fact that West Antarctica is losing mass at a significant rate suggests that the thinning ice shelves are already beginning to have an effect on ice discharge rates”.

4.3.2 Icebergs Calving

Ice sheet disintegration could lead to the nonlinear growth of ice discharge from Antarctica. Large icebergs have calved from Antarctic ice shelves more frequently in the three last decades in the warming context of West Antarctica (Kenneally and Hughes, 2006). The Antarctic Peninsula is one of the most interesting zones for climate change on the Earth. The recent excessive calving events started in 1989 in the West side of the Antarctic Peninsula (Doake and Vaughan, 1991) with disintegration of the Wordie Ice Shelf, followed by the George VI Ice Shelf in 1995 and the Wilkins Ice Shelf in 1998 (Scambos *et al.*, 2000[21]). In the east side of the Antarctic Peninsula, the Larsen Ice shelf started to disintegrate in 1995 (Rott *et al.*, 1996). This disintegration phenomena started in the Ronne Ice Shelf in 1986 (Ferrigno and Gould, 1987) and have been propagated in the Filchner Ice Shelf in 2002. In the Ross Ice Shelf, the recent calving of giant icebergs started in 1987 and culminated in the calving of giant iceberg B15A on 27 October 2005 (Keys *et al.*, 1998). Some of these phenomenons have been predicted by MacAyeal *et al.* (2008[22]), for the Ronne Ice Shelf in

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[19] www.geo.utexas.edu/.../Shepherd%20et%20al%20GRL%202004%20ASE.Pdf
[20] http://iopscience.iop.org/1748-9326/2/2/024002/fulltext see also http://www.wunderground.com/climate/Antarctica.asp, http://www.ossfoundation.us/projects/environment/global-warming/sea-level-rise/slr-research-summary-2008/2007_Hansen.pdf
[21] http://www.wunderground.com/climate/Antarctica.asp
[22] http://www.igsoc.org/journal/54/185/j07j053.pdf

2002. Lazzara *et al. (*1999) predicted the disintegration of the Ross Ice Shelf in 2000 and 2002 and associated it with rapid retreat of ice shelf grounding lines (Scambos *et al.*, 2008[23]). Figure 4.7 shows the iceberg B-15A break up off Cap Adare on 27 October 2005. The stations deployed on icebergs have been equipped with seismometers, automatic camera to observe the calving process and icebergs collision, GPS receivers and other sensors which operated during several years transmitting information about the integrity and behaviour of icebergs.

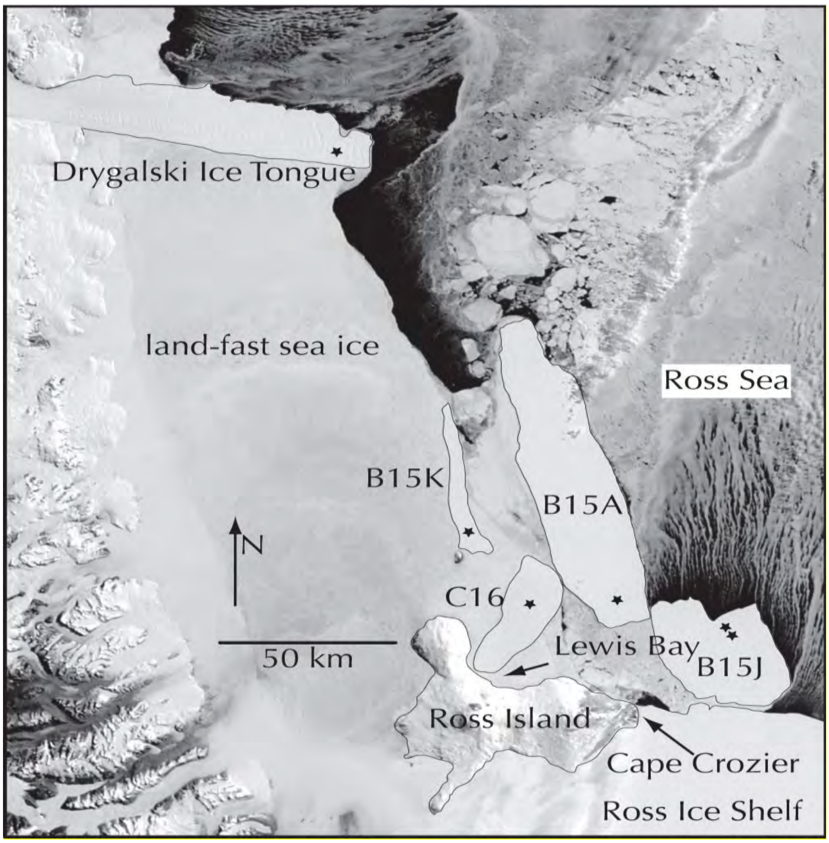

Figure 4.7 Location of Icebergs studied by the University of Chicago on 9 November 2004. The stars correspond to the stations deployed on icebergs and equipped with seismometers, automatic camera to observe the calving process and icebergs collision (credit MacAyeal *et al.*,[24] 2008 p. 372)

Figure 4.8 shows the radar image of B15A three days after iceberg break up.

[23] http://www.igsoc.org/journal/54/187/j08j007.pdf, http://www.igsoc.org/journal/54/185/j07j053.pdf
[24] http://geosci.uchicago.edu/research/iceberg_drift_research.shtml Figure 1

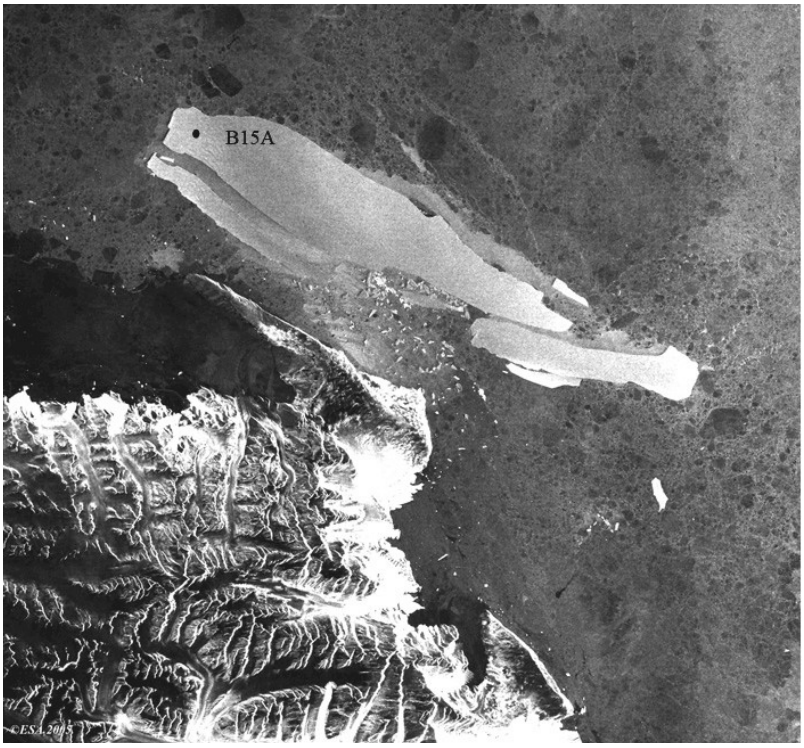

Figure 4.8 Radar Image on 30 October 2005 of the Tabular Iceberg B 15A Break up on 27October 2005, Cape Adare (credit Envisat radar image 30 October 2005, ESA[25], 2010 n.p.)

The iceberg B15A was 100 km long and 30 km large (300 km^3) when surveyed in October 2005 by researchers from Madison University (MacAyeal *et al.*, 2008). Large projects of iceberg transportation aims in terms of sizes this range of size of icebergs (See Chapter 7). The evolution of the firn temperature at 'nascent Iceberg' in anticipation of iceberg calving and located on the Ross Ice Shelf between 2006-2008 is shown in Figure 4.9. The temperature variation, transmitted by a thermistor deployed in the top 16 m of the firn layer at nascent iceberg is between -25°C at 16 m depth and 0°C at the surface.

[25] European Space Agency ESA http://geosci.uchicago.edu/research/iceberg_drift_research.shtml, http://www.esa.int/esaCP/SEMCYK638FE_index_0.html

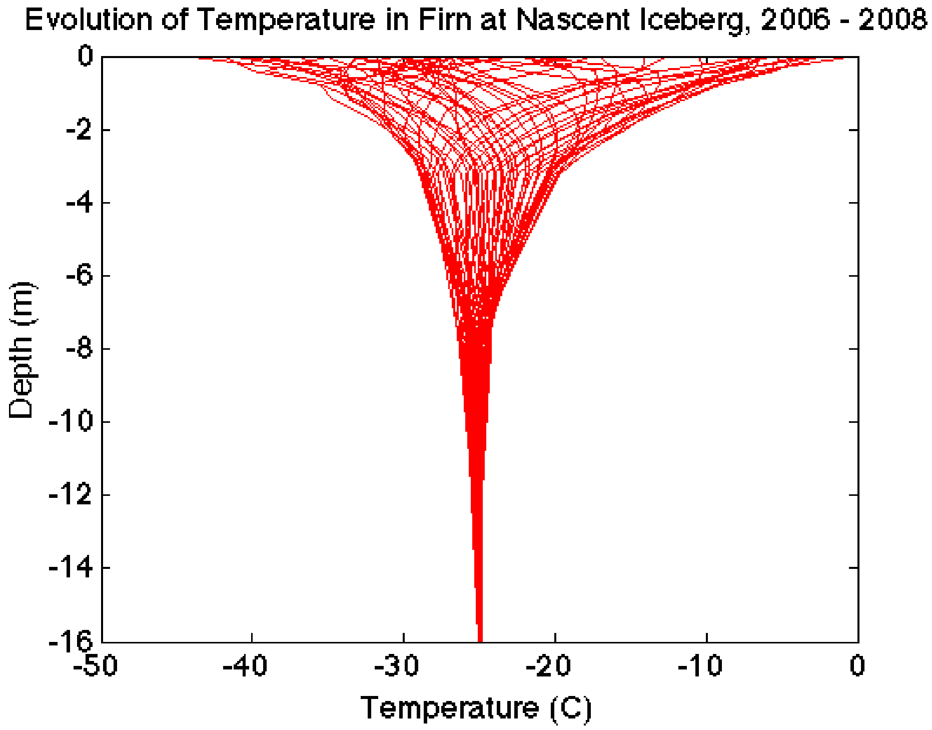

Figure 4.9 Temperatures in Firn between 2006-2008 in a Zone of Expected Nascent Iceberg (credit[26] 2010 n.p.)

According to Vaughan (2007[27] n.p.): "[D]uring the last half-century years the Antarctic Peninsula has experienced dramatic warming at rates several times the global mean".

The consequences of this warming are difficult to assess. Summer is particularly important to Antarctic terrestrial ecosystems that are hanging at the interface of ice and water. The climate warming and the potential collapse of the West Antarctic Ice Sheet have been simulated by computer models (Comiso, 2003; Turner and Solomon, 2007). According to such models, a collapse of the West Antarctica ice sheet is considered possible, if not highly probable, over the next few centuries. This collapse is predicted to result in a potential global sea level rise of about 5 m or more, if changes propagate into the east Antarctic ice sheet (Bindschadler and Bentley, 1997; Bindschadler, 1998). The time scale for this phenomenon is between 10^2 and 10^4 years (centuries or millennia).

The formation of glaciers which are the original source of tabular icebergs is a geological process that can take millions of years. The formation of drifting tabular icebergs is a

[26] http://geosci.uchicago.edu/research/iceberg_drift_research.shtml
[27] http://www.antarctica.ac.uk/bas-research/science/climate/antarctic-peninsula.php

perennial phenomenon in Antarctica. The use of several tabular drifting icebergs as a fresh water resource for Australia or for other countries would not have a significant impact on the geological processes of iceberg formation, or on physical processes in Antarctica. The number of icebergs taken from the system for this purpose would be very small. Indeed, the harvesting of icebergs would even respect their natural logic as a perennial phenomenon - they fall into the sea and they drift and melt away. If more icebergs are going to be released as an effect of climate change, iceberg transportation would help to minimise the resulting increase in global water levels (Bindschadler, 1998).

4.3.3 Icebergs Drifting and Melting

Antarctic tabular icebergs float with about 80% of their bulk submerged. Giant icebergs have a different melting pattern than that of smaller icebergs, due to the mass of ice, size, and relation between surface and volume. According to Silva *et al.* (2006[28] p.1) “an estimated 35% of giant icebergs' mass is exported north of 63° S versus 3% for smaller bergs, although giant bergs spend more of the earlier part of their history nearer to the coast”. Tabular icebergs have an important role in the freshwater budget of the ocean, on the amount and distribution of free water. The contribution of giant icebergs to the Southern Ocean freshwater flux was estimated by combining information from a database of iceberg tracks (Hult and Ostrander, 1973) with a model of iceberg thermodynamics developed by Silva *et al.* (2006). According to Silva *et al.* (2006[29] p.1), “[I]n the period 1979-2003 the mass of “giant” icebergs (icebergs larger than 18.5 km in length) calving from Antarctica averaged 1089 ± 300 Gt yr^{-1} of ice”.

This value given by the IPCC (2007) is half of the value of snow accumulation over the continent (2,246 ± 86 Gt yr^{-1}). The average melt water input can exceed the precipitation minus evaporation ratio (P - E) in certain areas. In the warming area of the Antarctic Peninsula, more and more icebergs are released with related large episodic carvings. Changes in sea ice extent and ice movements would affect the extent of winter sea ice, which over 1979-2003 has declined in area and duration in the West Antarctic Peninsula where around 80% of life in the Antarctic occurs.

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[28] http://www.agu.org/pubs/crossref/2006/2004JC002843.shtml
[29] http://www.agu.org/pubs/crossref/2006/2004JC002843.shtml

Icebergs, in addition to being large floating ice volumes, contain scours, rock mass eroded by the action of glaciers. Icebergs moving, breaking up and melting away from Antarctica carry a large burden of rock. Ice rafted debris gouged from the underlying land surface is dropped onto the sea floor and set down on the sea bed. Scours carried by icebergs and deposited on the sea floor can exhibit a large range of sizes. Icebergs can transport 50 million t/year. In the Arctic, scours have been reported up to 1 km in length (Mertz, 2005; Syvitski *et al*., 2001). The ability of icebergs to transport sediments and scour the sea floor, as well as the Heinrich Events (Heinrich, 1988) are processes which all have the ability to affect the sedimentary record in polar seas (Whillans and Bindschadler, 1988). Heinrich Events consists in a release (related to warming climatic conditions) of an exceptional quantity of icebergs containing sediments of eroded minerals and leaving debris on the sea floor as they melt. At areas adjacent to and beneath the foot of a glacier, sediments are periodically disturbed by the calving of icebergs from the glacier and related scouring (Smale *et al.*, 2008). The icebergs melting in open seas have consequences on the nutrient provisioning. Glacial deposits cease at about 60° S and are replaced by a 200 km zone of yellow diatom ooze[30]. In a zone from the continent to the northern limit of the pack ice, benthic sediments are nearly all ferruginous in origin. Small areas of diatom sponge spicules or recent volcanic deposits are present within this ferruginous zone (Dayton *et al*., 1969). According to Brown (2008 n.p.[31]), “Many factors influence the probability of an iceberg impacting on an area of seabed. These include depth, seabed topography, proximity to an iceberg source, wind direction and tidal regimes”. According to McLamb (2008[32] n.p.): “Antarctic icebergs can affect marine life as deep as 500 m”. In addition to the mechanical effects of icebergs on the continental margins, they can also introduce nutrients or carbon to their environment as can be seen from Figure 4.10

[30] Deep Sea Drilling Project Initial report vol 29, site 280, pages: 225 – 271 n.d. www.deepseadrilling.org/29/volume/dsdp29_07.pdf
[31] http://www.sciencedaily.com/releases/2008/07/080717140451.htm
[32] http://ecology.com/ecology-today/2008/12/03/antarctic-icebergs-affecting-marine-life-as-deep-as-500-meters/

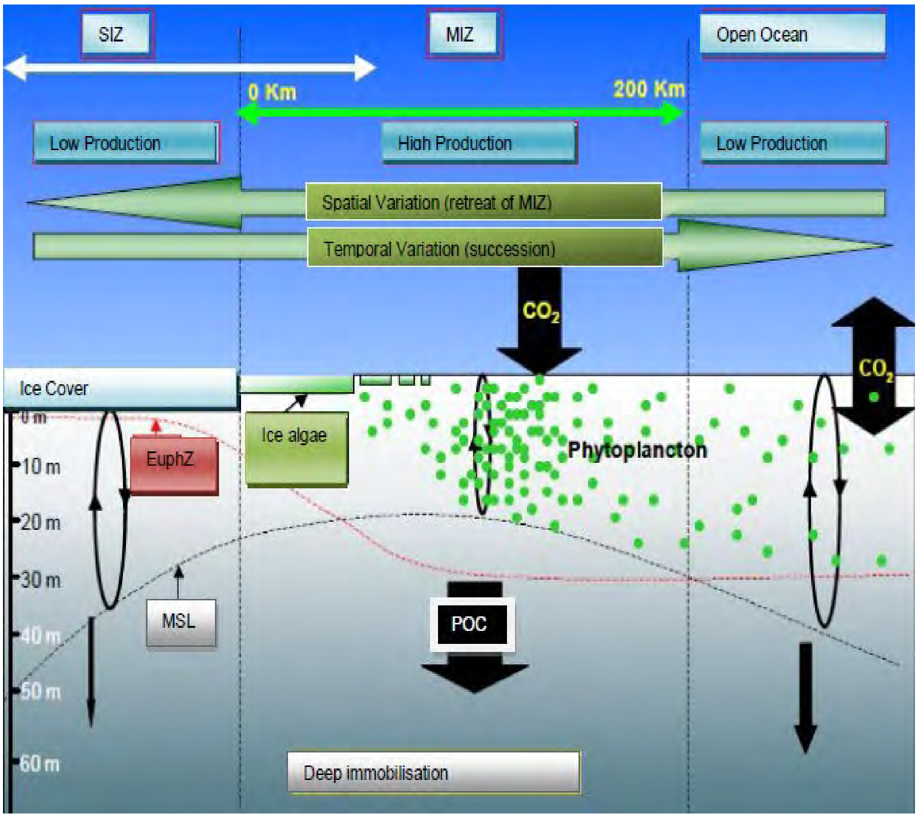


Figure 4.10 Processes in the Marginal Ice Zone (MIZ) POC: Particular Organic Carbone, MSL: Mixed Surface Layer, EuphZ: Euphotic Zone (1% of light); SIZ: Seasonal Ice Zone (credit adapted from Ferreyra *et al*., 2004[33] p. 4)

In this figure three zones are illustrated: the seasonal ice zone, covered with seasonal ice, the marginal ice zone and the open ocean. The distance between the ice cover zone and the open ocean can be 200 km. In the ice covered zone, there is a very low production of algae because only 1% of daylight can penetrate. In the MIZ a high production of phytoplankton was observed because of the decreasing POC, the spatial and temporal variation of ice cover and the increasing CO_2 supply. As expected, in the “open ocean” zone, low production of algae was observed.

The availability of free water in sea ice affects the type and number of marine living organisms found on the seabed and may cause changes in the distributions of key species (Dayton *et al*., 1969).

[33] vertigo.revues.org/3172

The cooling and nutritional effects of sea ice vary seasonally (Figure 4.11). In summer time (June, July and August, in the Northern Hemisphere) the daylight penetrating into the sea water, generates optimal life conditions for zooplankton and phytoplankton (Schwarz and Schodlok, 2008[34]; Vernet *et al.*, 2009[35]).

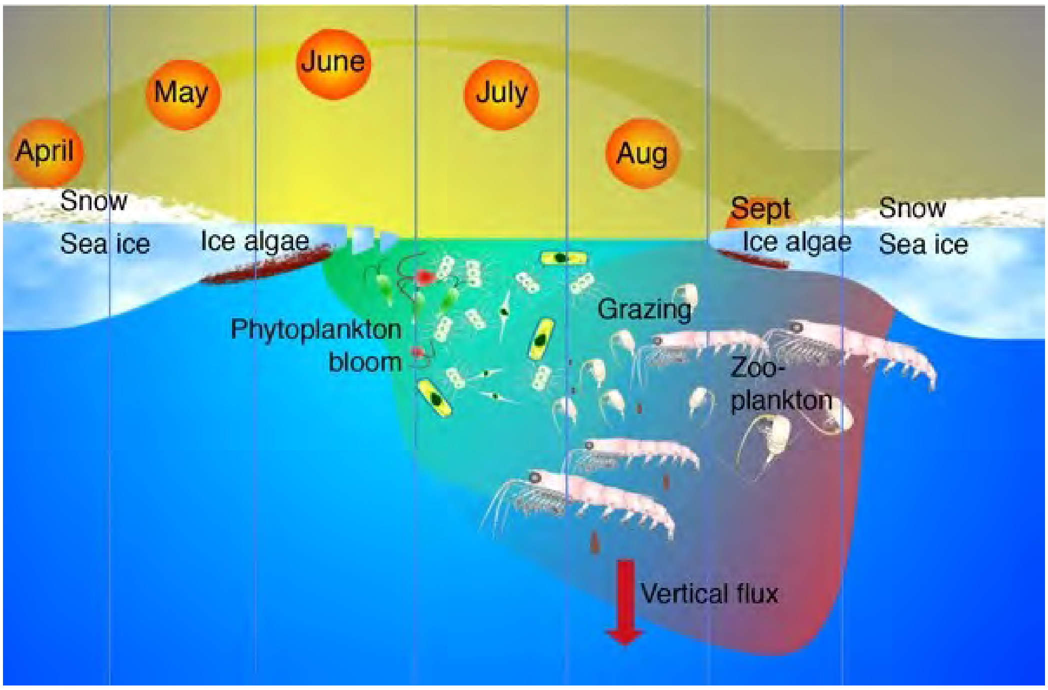


Figure 4.11 Plankton and Seasons in the Northern Hemisphere
(credit Keck and Wassmann 1993, Strand, University of Tromsø[36] 2008 n.p.)

As in the Northern Hemisphere, in the Southern Hemisphere there is a rich life of zooplankton and phytoplankton under the sea ice, varying with the seasons. A specific freshwater circulation system exists in icebergs which is ecologically important for benthic nutrition. Icebergs shelter krill and indirectly some fish species. By modifying the temperature, the salinity, and the day light transmitted into the sea ice and sea water, icebergs drifting on the Southern Ocean have an important impact on living environments.

Figure 4.12 shows the maximal and minimal extension of ice and the Antarctic Zones described as: SAF (Sub-Antarctic Front), APF (Antarctic Polar Front), PACZ (Polar Antarctic Cold Zone), POOZ (Permanently Opened Ocean Zone). Icebergs harvesting would be most

[34] http://precedings.nature.com/documents/1706/version/1/files/npre20081706-1.pdf
[35] http://polarphytoplankton.ucsd.edu/docs/publications/papers/Vernet_MS_%20Icebergs_Subm042710.pdf
[36] www.arcticsystem.no/.../primaryproducers.html

appropriate in the outer limits of the Polar Antarctic in the limit of Polar Antarctic Cold Zone. In this zone the impact on the local ecosystem would be minimal because of the absence of sea ice and dependent organisms.

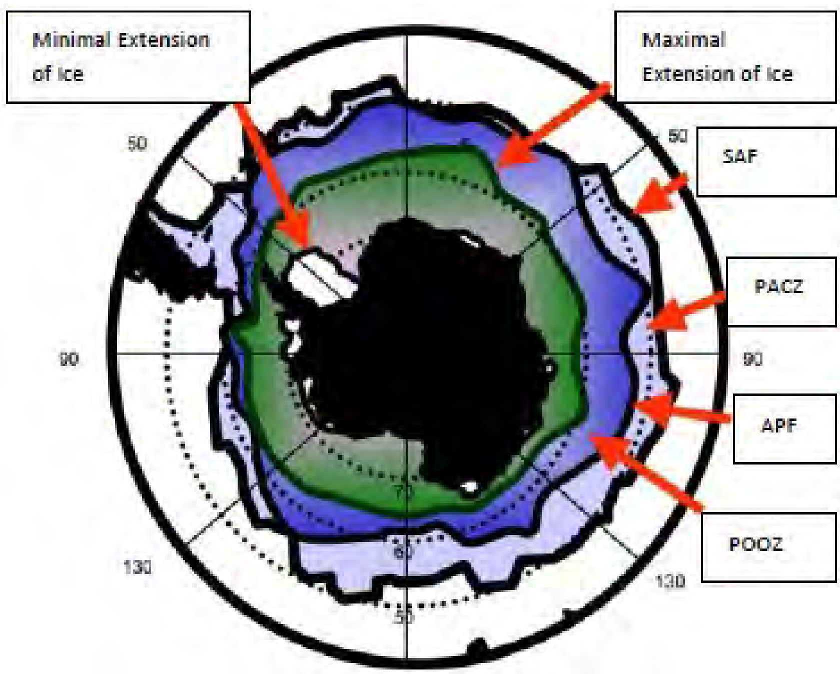


Figure 4.12 Antarctic Zones: SAF (Sub-Antarctic Front), APF (Antarctic Polar Front), PACZ (Polar Antarctic Cold Zone), POOZ (Permanently Opened Ocean Zone) (credit adapted from Orsi *et al*., 1995, NASA in Ferreyra *et al*., 2004[37] p. 4)

4.4 Icebergs Impacts on Environments

In the proximity of icebergs the following effects are observed:

- decreasing sea and air temperature (Sachs, 2005);
- direct flora and fauna impacts: change of vegetation with temperatures cooling (Grimm *et al*., 1993) or scouring;
- change in fauna with cooling temperatures (Grousett *et al*., 2000), flux in planktonic isotopic make-up (due to changes in $\delta^{13}C$, decreased $\delta^{18}O$);
- oceanic salinity decreasing due to the influx of fresh water;
- decreasing mammals abundance related to reduced salinity (Bond *et al*.,1992);
- deposition rates relative to background sedimentation (Heinrich, 1988);

[37] vertigo.revues.org/3172

- increased terrigenous runoff from the continents, and stronger winds (Porter and Zhisheng, 1995);
- the spring depletion of ozone over Antarctica has been implicated in driving atmospheric circulation change (Thompson and Solomon, 2002);
- changes in ocean current velocity (Roche *et al*., 2004);
- rising sea ice volume (Bar-Matthews *et al*., 1997).

The environmental impacts of icebergs can be local near the coasts, regional - for example in the west Antarctic Peninsula, and in the 'high seas' - 200 km from the coasts. (Table 4.1)

Table 4.1 Summary of Iceberg Impacts in Antarctica

	Icebergs impacts in Antarctica		
	Local scale	**Regional scale**	**High sea**
Effects	Scouring, cooling, ferruginous sediments, duration of winter sea ice and tidal regimes.	Wind direction, current regime, cooling, ferruginous sediments, duration of winter sea ice.	Wind direction and current regimes, ferruginous sediments, melting pattern.
Range	10 km range, deep as 500 m, nearer to the coast	Ferruginous zone 60° S	200 km zone
Impact Intensity	About 65% of coastal fish species (*Notothenioidei,Bathidraconidae,Channichthyidea, Harpagiferidae*) are confined to Antarctic high latitudes. Smaller bergs dominate.	West Antarctic Peninsula where the majority of the Antarctic life occurs (80%).	35% of giant icebergs melt north of 63° S ' and release sediments 5 km away from icebergs.
Comment	Ecosystems are fragile and numerous. Iceberg scouring has important effects.	Some regions are more fragile. The ferruginous sediments of icebergs are important resources.	In the open seas, the most relevant potential impact is determined by the icebergs nutrient provisioning function.

The intensity of local, regional and high sea impacts is also related to climatic change in Antarctica and will be discussed in the next section.

4.5 Icebergs and Climate Change in the 20th Century

The 20th Century has been characterised by unprecedented climate change, which is often synonymous with global warming. The United Nations Convention on Climate Change

(1994 [38] n.p.), which is an international framework for governments to cooperate for adaptation to the impacts of climate change, defines climate change as:

> [a] change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.

The UN Convention on Climate Change entered into force on 21 March 1994. Encyclopaedia Britannica noted that global warming expressed by the global average surface temperature had resulted from the greenhouse effect and primarily from air pollution. It was forecast that by 2100 global average surface temperature would increase by from 1.8°C to 4°C, depending on the greenhouse gas emission scenario, produced by human activities such as industrial processes and transportation. In this case the term anthropogenic climate change is used and refers according to Zaitseva (2009[39] n.p.) to:

> [a] significant change (such as a change having important economic, environmental and social effects) in the mean values of a meteorological element (in particular temperature or amount of precipitation) in the course of a certain period of time, where the means are taken over periods of the order of a decade or longer.

In my thesis I will refer to this definition of climate change.

In a more general climatologic framework, climate change is a long-term evolution in the statistical distribution of weather modes for set ranges of temporal and spatial scales (decades, centuries, millions of years). Terrestrial climate change may result from changes in solar activity, changes in the Earth's orbital characteristics or natural internal processes of the climate system. Furthermore, it is important to measure this change, determine the consequences of the climate change, to predict the process of change and to provide appropriate responses.

Glaciers are the most relevant indicators of climate change, being the most sensitive and easy to survey by aerial photography and satellites (since the 1980s) with for example the NASA Earth's applied science program. Over recent decades, Antarctica and Greenland have experienced climate changes that can be measured by changes in air temperature,

[38] http://unfccc.int/essential_background/convention/background/items/2536.php
[39] http://nsidc.org/arcticmet/glossary/climate_change.html

mass balances, sea ice extent, and ocean levels (Bromwich, 1988; Bamber and Payne, 2004; Overland *et al*., 2008).

According to Turner *et al.*, (2005[40]), meteorological data published by Antarctic research stations and data from different International Geophysical Years, (which started in 1958, the last was in 2008) indicated that the western side of the Antarctic Peninsula has experienced one of the largest measured annual near-surface warming in the world.

In my thesis I am particularly concerned to study climate change in Antarctica. It could have a significant impact on the Antarctic ecosystem, sea ice and icebergs. The physical parameters used to express the degree of climate change are: air, land and sea temperatures, the mass balance of ice and changes in sea level. These parameters will be discussed in the following sections.

4.5.1 Changes in Temperature

Changes in temperature in Antarctica, have been registered by different polar expeditions and consistently, by Antarctic Stations and by satellites. The meteorological satellites in geostationary orbit have been operational for two decades[41]. The temperatures of land and ocean surface are provided by meteorological data delivered by the United States NOAA - operational polar orbiting satellites (WMO n.d. n.p.[42]).

In what follows I will discuss global temperature changes and temperatures changes in Antarctica.

a. Global Temperature Changes

Over the last 40 years the average land, ocean surface and air temperatures have increased significantly. From Figure 4.13 which shows the annual average temperatures since 1860 to 2005, a tendency of increasing temperatures is observed.

[40] http://www.scar.org/researchgroups/physicalscience/reader_turneretal.pdf
[41] CGMS - Coordination Group for Meteorological Satellites
DMSA - Directory of meteorological satellites applications
EUMETSAT - The European Organisation for meteorological satellites
[42] http://www.wmo.int/pages/prog/sat/CGMS/Directoryofapplications/en/cover.htm

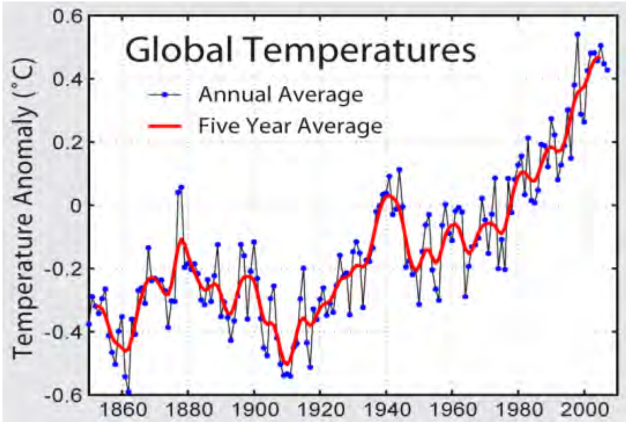


Figure 4.13 Record Global Average Temperatures (credit Brohan *et al.*,[43] 2006 n.p.)

Figure 4.14 illustrates global land-ocean temperatures anomalies (°C) since 1880 to 2008.

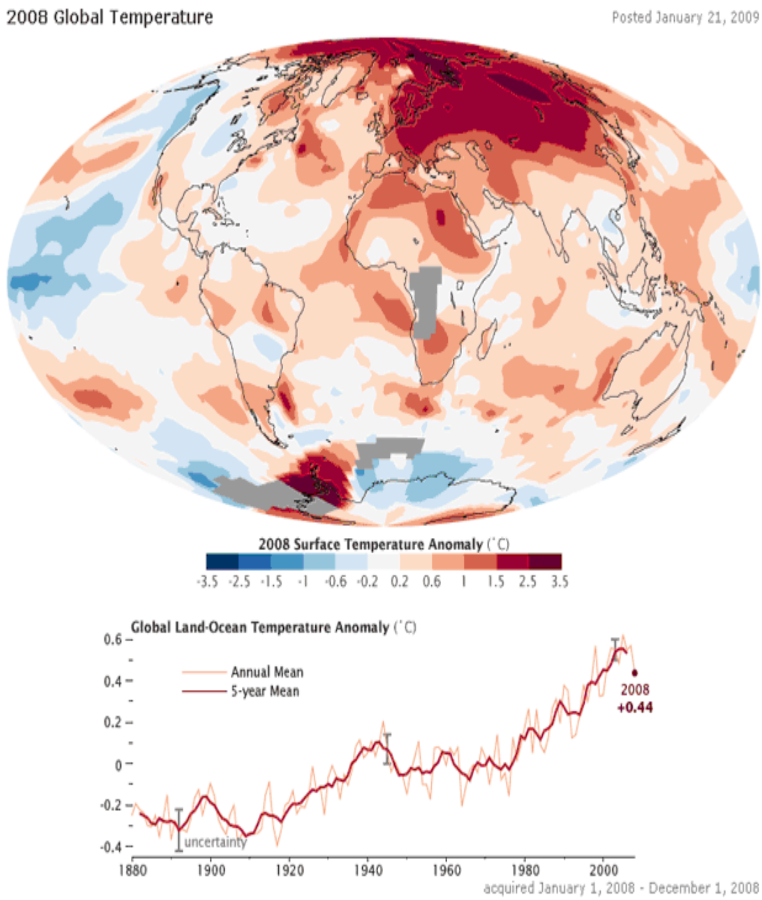


Figure 4.14 Global Land-Ocean Temperatures Anomalies (°C) since 1880 to 2008 (credit Weather underground[44], 2008 n.p.)

[43] www.michaelmandeville.com/earthchanges/gallery/Climate/orbital_cycles.htm

In 2008 the average increasing in global temperature anomalies was +0.44°C. In the Antarctic Peninsula, surface temperatures anomalies were relatively high, namely +3.5°C. When the temperatures anomalies on the Northern and Southern Hemispheres are compared, it seems that the Southern Hemisphere has fewer anomalies as can be seen from Figure 4.15 and Figure 4.16.

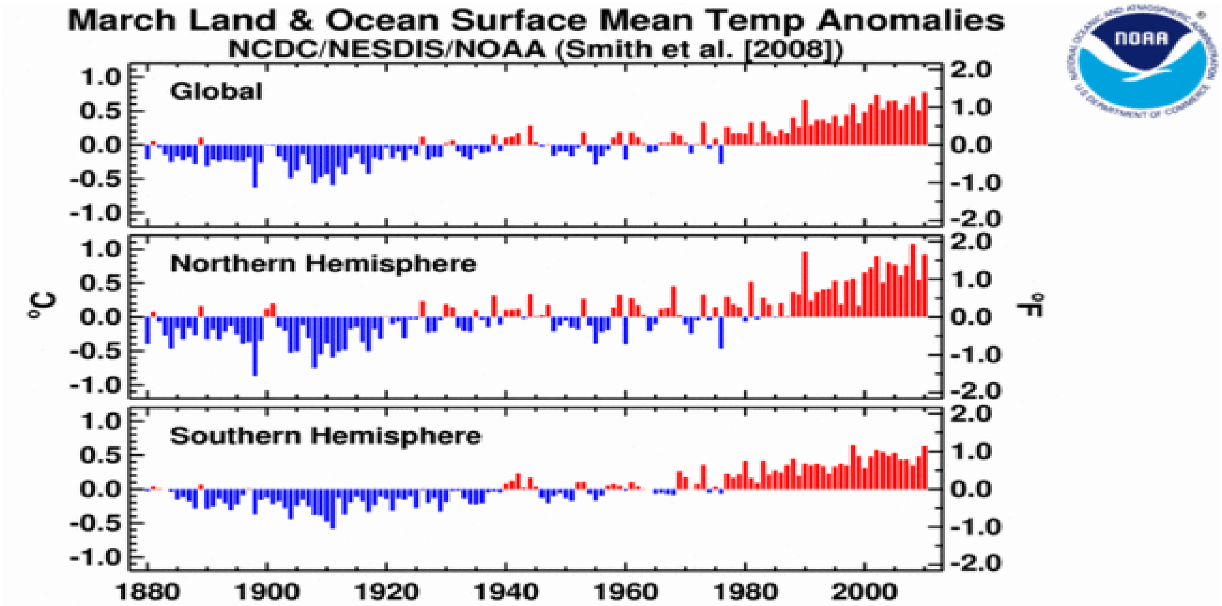


Figure 4.15 Temperatures Anomalies on Northern and Southern Hemispheres, compared with global temperatures (credit NOAA Smith *et al.*,[45] 2008 n.p.)

McIntyre (2007) calculated temperature variations per decade (°C/decade) between 1985 and 2005 from the satellite data published by Spencer and Christy and concluded that in North Pole zone there is a warming tendency of 0.497°C/decade (Figure 4.19).

[44] http://www.wunderground.com/hurricane/2009/2008.png
[45] http://global-warming.accuweather.com/marchanom-thumb.gif

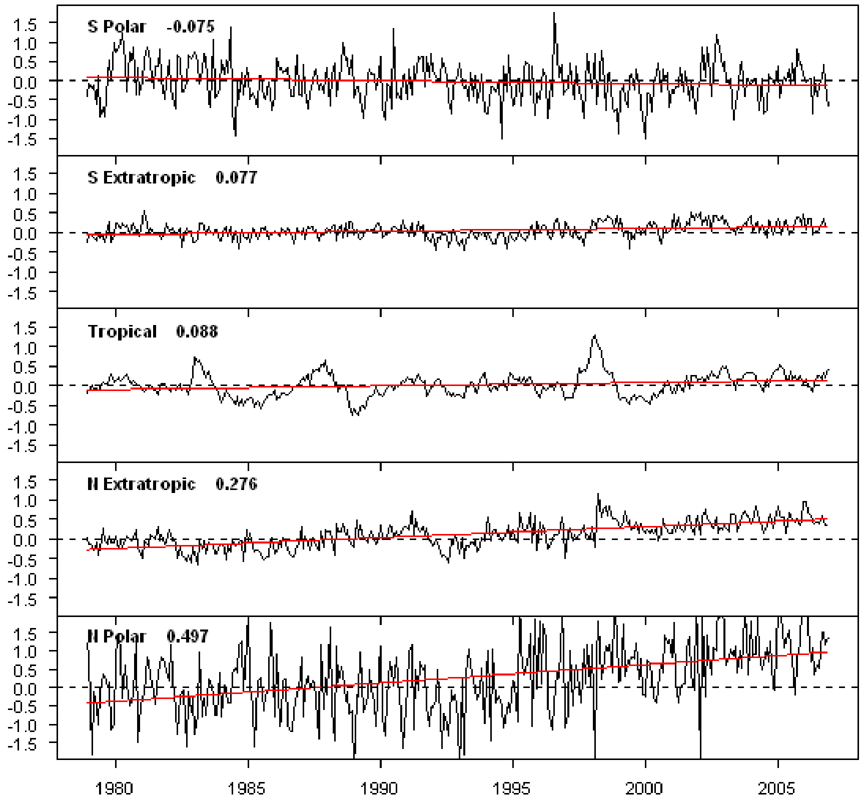


Figure 4.16 Satellite Temperatures for Ocean Latitudinal Bands from MSU (credit McIntyre[46], 2006 n.p.)

In the South Pole region no significative temperature variation was observed (-0.075°C/decade). To understand climate evolution in a broad perspective, Clark *et al.*, (1999[47]) reviewed the deglaciation in the Northern Hemisphere and noted the millennial climate changes as cited (p. 149) below:

> Orbitally induced increase in northern summer insulation after growth of a large ice sheet triggered deglaciation and associated global warming. Ice-albedo, sea level, and greenhouse-gas feedbacks, together with tropical warming from weakening winds in response to polar amplification of warming, caused regional-to-global synchronisation of deglaciation. Effects were larger at orbital rather than millennial frequencies because ice sheets and carbon dioxide vary slowly. Ice-sheet-linked changes in freshwater delivery to the North Atlantic, and possibly free oscillations in the climate system, forced millennial climate oscillations associated with changes in North Atlantic Deep Water (NADW) flow. The North Atlantic typically operates in one of three modes: modern, glacial, and Heinrich. Deglaciation occurred from a glacial-mode ocean that, in

[46] http://vortex.nsstc.uah.edu/data/msu/t2lt/uahncdc.lt
[47] http://earthscience.ucr.edu/gcec_pages/docs/geo224/Alley%20and%20Clark%201999-AnnRevEPS-The%20Deglaciation%20of%20the%20Northern%20hemisphere.pdf

comparison to modern, had shallower depth of penetration of NADW formed further south, causing strong northern cooling and the widespread cold, dry, and windy conditions associated with the glacial maximum and the cold phases of the millennial Dansgaard-Oeschger oscillations. The glacial mode was punctuated by melt water-forced Heinrich conditions that caused only small additional cooling at high northern latitudes, but greatly reduced the formation of NADW and triggered an oceanic "seesaw" that warmed some high-latitude southern regions centred in the South Atlantic.

In a very large time context, it seems that the warming during the past century studied by Labitzke and Shindell (2008) since 1895 probably have been overestimated. Scafetta and West (2007) in their study on the temperature record since 1600 report the same tendency to over-estimation. Data from the Global Ocean Surface Temperature Atlas reveals air temperature has been warming by approximately 0.2°C/decade for the past 30 years. Data collected by eight scientific organisations (among them CSIRO), since 1900 to 2000 and global warming projections 2000-2010 are shown in Figure 4.19.

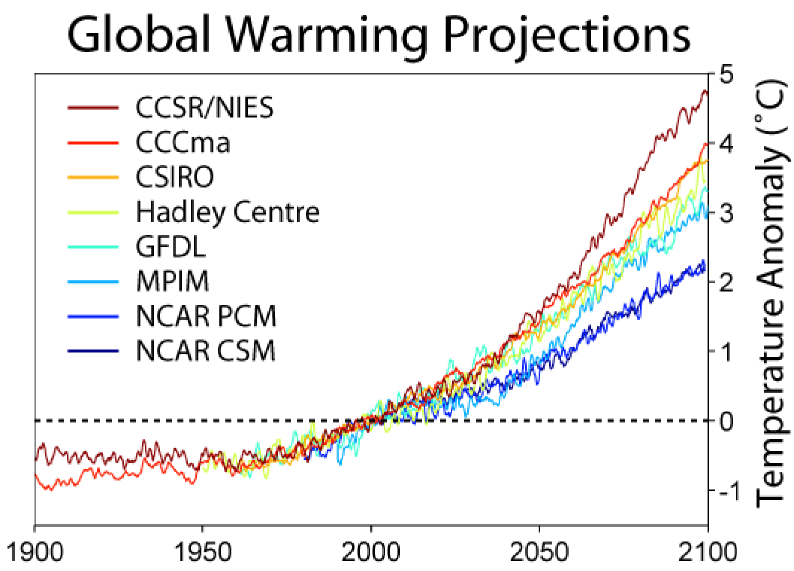


Figure 4.17 Global Warming Projections 2000-2100 (credit IPCC[48], 2007 n.p.)

However, the extent to which this warming is related to natural exothermic sources is largely unknown. Changes in solar radiation, in atmospheric transmission of solar radiation, in global surface, pressure fields and in the solar magnetic field are the main factors affecting global maritime temperature variations (Newell *et al.*, 1989, Wu *et al.*, 1990, McIntyre, 2007).

[48] commons.wikimedia.org/wiki/File:Global_Warming-Predictions.png

Warming depends on changes in the southern annular mode (Marshall *et al*., 2004). According to a UK report (ATCM 2008 XIII, p. 4[49]) "warming does appear to be correlated with atmospheric circulation (van den Broeke and van Lipzig, 2003)"; D'Aleo *et al.*, (2009[50]) has argued that the total solar effect may be responsible for a substantial part of the warming since 1900. The prediction of global warming by modelling has been confirmed by experimental observations. From this literature I have selected the following examples:

- global warming: models have been proposed by Arrhenius (1896), Callendar (1938), Plass (1956), Sawyers (1972) and Broecker (1975). These models have been confirmed by Crowley (2000), Philipona *et al.* (2004), Evans and Puckrin (2006), Lean and Rind (2008), Mann *et al.* (2008);
- the Artic warms more than Antarctica and phenomena related to Antarctica: models have been proposed by Arrhenius (1896) and Manabe and Stouffer (1980). These models have been confirmed by: Fyfe *et al.* 1999, Doran *et al.* 2002, McKnight *et al*. 2002, Comisso 2003, Turner *et al.* 2007;
- tropical green house effect: a model has been proposed by Vonder Haar (1986). This model had been confirmed by Lubin (1994) ;
- increased coastal up welling of ocean water: a model have been proposed by Bakun (1990) and confirmed by Goes *et al.* (2005) and McGregor *et al*. (2007).

b. Temperature Change in Antarctica

To study temperature change in Antarctica, it is necessary first to study temperatures in the Southern Ocean around this continent. In Antarctica the current trends are due to temperature changes in the oceans, on land surfaces and in the air. The global ocean temperature measured between the surface and 700 m depth has risen by 0.1°C in the last 70 years (IPCC, 2007). The same trend has been observed in the Southern Ocean, at 900 m depth, from 1930 to 2000 which has on average experienced an increase in temperature of around 0.01°C. From Figure 4.18 it can be seen that while some areas (zones in blue) have experienced a decrease in temperature, other areas (zones in red, yellow and orange) have experienced an increase in temperature with maximum 0.40°C/year.

[49] www.ats.aq/documents/ATCM31/ip/ATCM31_ip050_e.doc
[50] http://www.aai.ee/~olavi/ISPM-app2f.pdf, http://icecap.us/images/uploads/US_Temperatures_and_Climate_Factors_since_1895.pdf

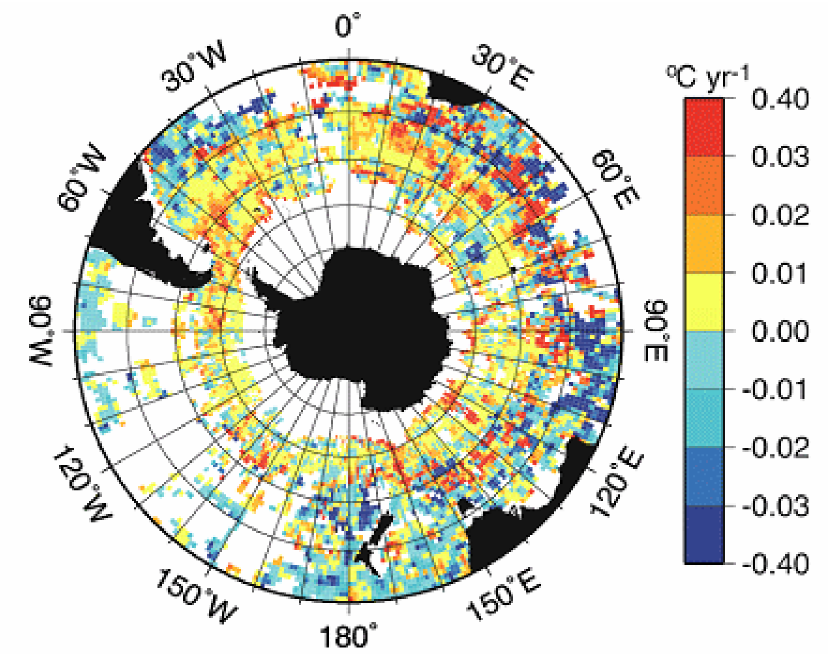


Figure 4.18 Temperature Trends in Southern Ocean at 900 m Depth from 1930 to 2000 (credit IPCC[51], 2007 n.p.)

Unlike the continent's interior, Antarctica's coastal areas and western zone have undergone significant rises in temperature over recent decades (Figure 4.19 and Figure 4.20).

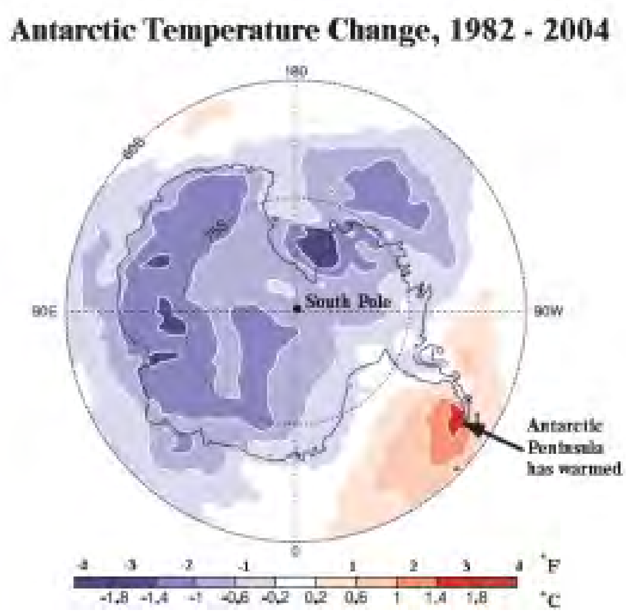


Figure 4.19 Antarctic Yearly Surface Temperature Changes 1982/2004 (credit IPCC[52], 2007 p. 293)

[51] icons-ecast.wxug.com/.../temperature-trends.gif/

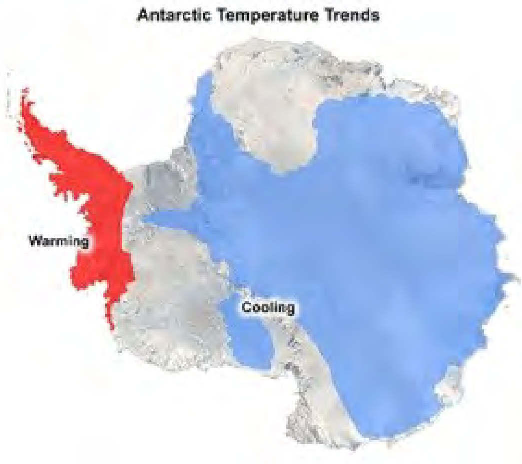


Figure 4.20 Approximate Boundaries of Antarctic Areas Warmed or Cooled over the past 35 years, Deyo, University Corporation for Atmospheric Research UCAR (credit UCAR[53], 2007 n.p.)

Mean annual temperatures in the Antarctic Peninsula have increased by up to 2.5°C since the 1950s (Conway *et al*., 1999; Turner *et al*., 2006). Climate scientists, Vaughan *et al*. (2003[54]) and Fox and Cziferszky (2008) reported that this warming represents the most rapid average annual surface temperature rise of anywhere on the planet (Figure 4.21).

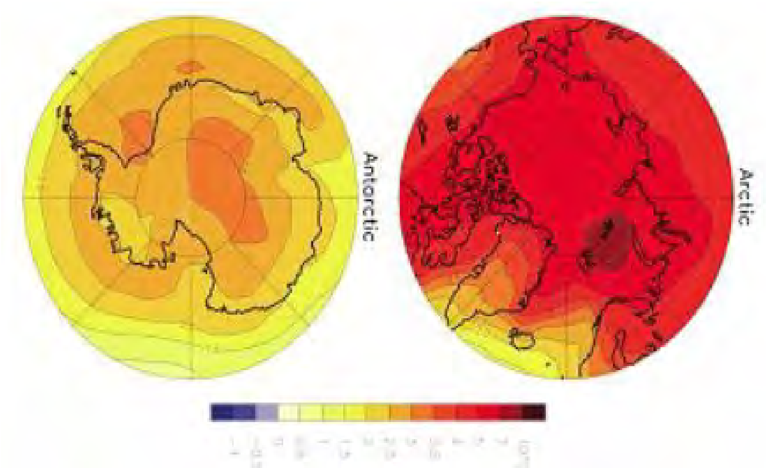


Figure 4.21 Annual Surface Temperature Change between 1980-1999 and MMD-A1B Projections 2080-2099 for the Antarctic and the Arctic (credit IPCC[55], 2008 n.p.)

[52] http://www.ipcc.ch/ipccreports/ar4-wg1.htm , http://www.wunderground.com/blog/JeffMasters/comment.html?entrynum=1178, http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter3.pdf
[53] www2.ucar.edu/news/941/climate-models-overheat-antarctica-new-study-find#mediaterms 2007
[54] http://www.wunderground.com/climate/Antarctica.asp
[55] www.arabic.wunderground.com/climate/Antarctic.asp

Figures 4.22 and 4.23 show the temperature change in Antarctica over the past two decades.

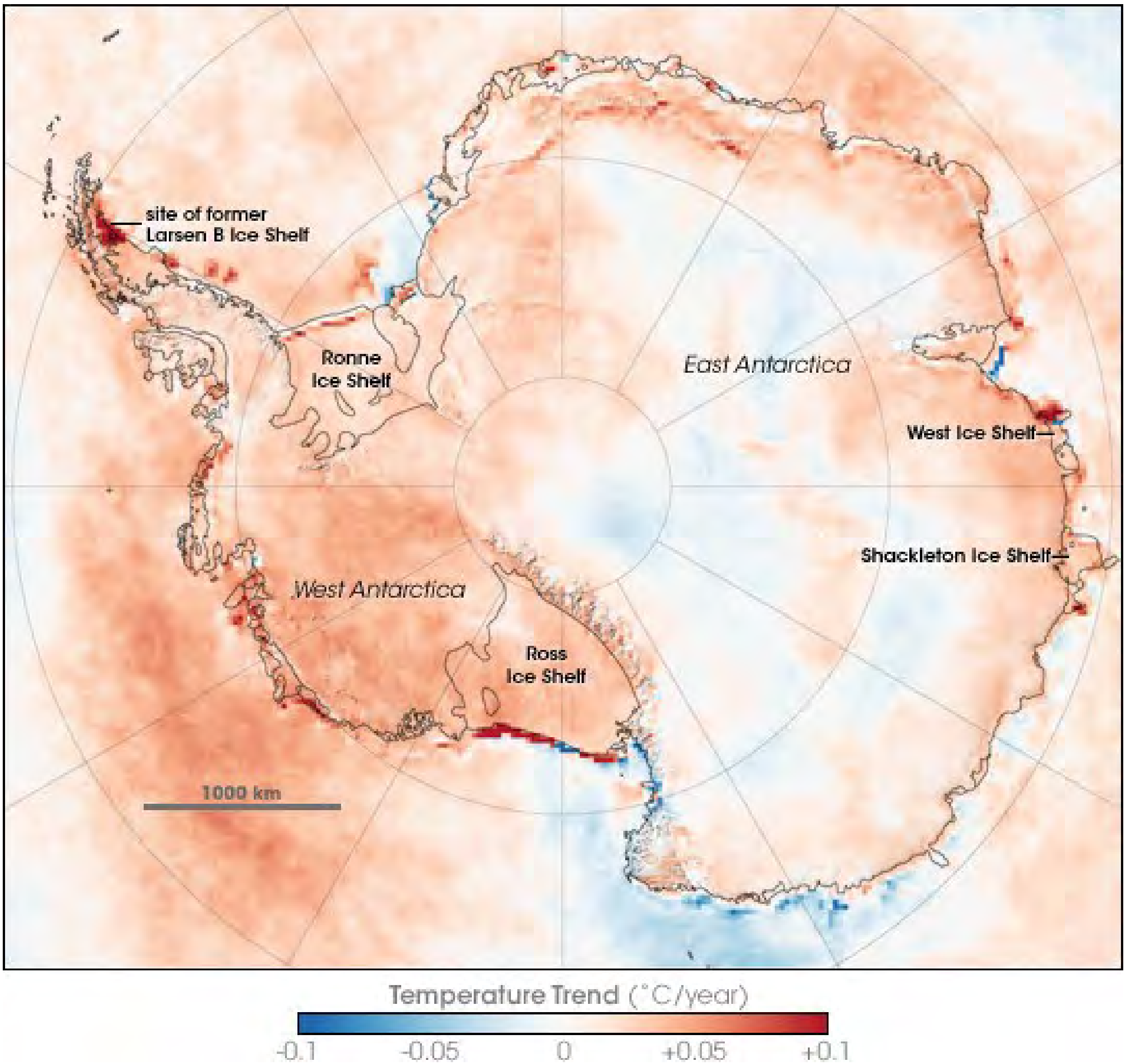


Figure 4.22 Two Decades of Temperature Change in Antarctica (credit Simmon, based on data from Comiso, GSFC 2007[56] n.p.)

56 http://earthobservatory.nasa.gov/IOTD/view.php?id=8239

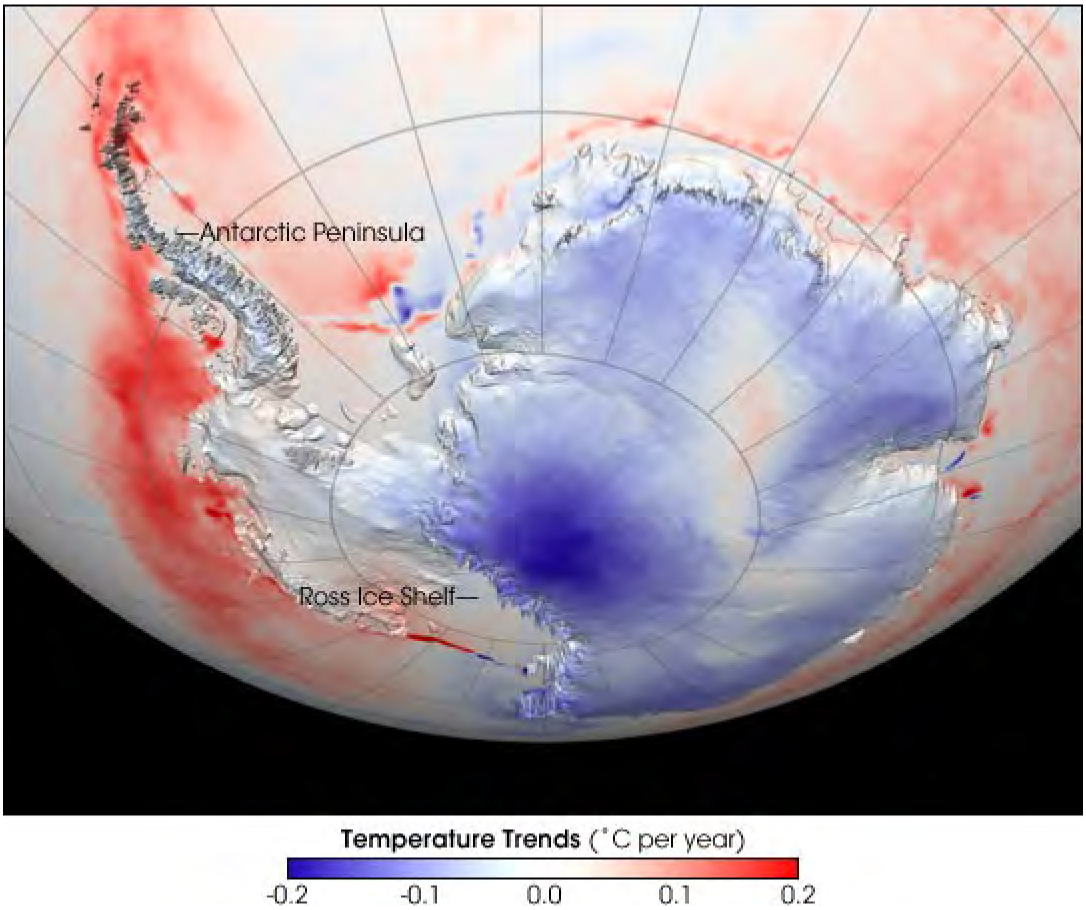


Figure 4.23 Antarctic Temperature Trend 1982-2004 (credit Comiso, NASA-GSFC 2006[57] n.p.)

Turner (2006) based on meteorological data published by Antarctic research stations and data from different International Geophysical Years (which started in 1958, the last was in 2008), indicated that: “the western side of the Antarctic Peninsula has experienced the largest measured annual near-surface warming in the world”.

As an example, at the Ukrainian-run Faraday/Vernadsky Research Station located off the west coast of the Antarctic Peninsula in the Wilhelm Archipelago, an average temperate increase of about 0.55°C per decade has been recorded (Comiso, 2000).

However, few temperature changes occurred at the surface across the rest of the Antarctic continent. Doran *et al*. (2002) reported a slight cooling in recent decades which contradicts the increase of 0.11°C per decade of near-surface temperatures across the Earth since the

[57] http://earthobservatory.nasa.gov/IOTD/view.php?id=6502

1950s (Turner *et al*., 2006). However, in recent projections for 2080-2099, the IPCC expects temperatures to rise (IPCC, 2007; see also Figure 4.21).

The Antarctic Peninsula differs from other regions in Antarctica by having a summer melting season. The number of days per year during which the melting of ice occurred in the last decade increased by 74% in the Antarctic Peninsula (Scambos *et al*., 2003). The warming experienced by the Antarctic Peninsula is supposed to be a regional manifestation of the greenhouse effect (Lubin, 1994). The Antarctic Peninsula is an area of rapid climate change and has warmed faster than anywhere else in the Southern Hemisphere over the past half century (Fyfe *et al.*, 1999; Turner, 2007). Climate records from the west coast of the Antarctic Peninsula show that air temperatures in this region have risen by nearly 3°C during the last 50 years (BAS, 2007). The West Antarctic Ice Sheets temperature fluctuates in response to changes in ocean temperature, which underlies most of the ice sheet in this region (Scambos *et al.*, 2003[58]).

Contemporary scientific understandings of the consequences of the Antarctic Peninsula warming are contradictory and hence difficult to assess.

According to the UK information paper of ATCM XIII (2007 p. 4):

> Notwithstanding the uncertainty of whether climate warming will continue, it is reasonable to suppose that continued warming over the summer would cause substantial regional impacts such as the retreat of coastal ice and the loss of snow cover [which could provide new habitats for expanding flora and fauna].

Two decades of marine ecosystem monitoring the Peninsula have revealed transformation at various trophic levels (McKnight *et al.*, 2002). A reduction in sea ice affects the entire Antarctic ecosystem. In particular according to the UK information paper of ATCM XIII (p. 4) Atkinson *et al*. (2004) reported that: “the balance between krill and salps, the main grazers of phytoplankton. The loss of krill has impacts on higher predators like albatrosses, seals, whales and penguins”.

Walsh *et al*. (2001) have researched the impact of carbon dynamics on the Southern Ocean phytoplankton community. They found that the role of light and grazing is demonstrated in affecting both sequestration of atmospheric CO_2 and food availability to larval krill (Pollard *et*

[58] http://web.pdx.edu/~chulbe/science/reprints/ScambosHulbeFahne_ARS03.pdf

al., 2009[59]). Phytoplankton converts CO_2 to organic carbon. The conversion requires nutrients such as nitrogen, phosphorus, silicon and iron (Geibert *et al.*, 2010[60]). CO_2 is remineralised in Deep Ocean. 38 × 10^{18} g of carbon is stored in deep oceans. Phytoplankton bloom acts as a biological pump for the sequestration of atmospheric CO_2 (Figure 4.24).

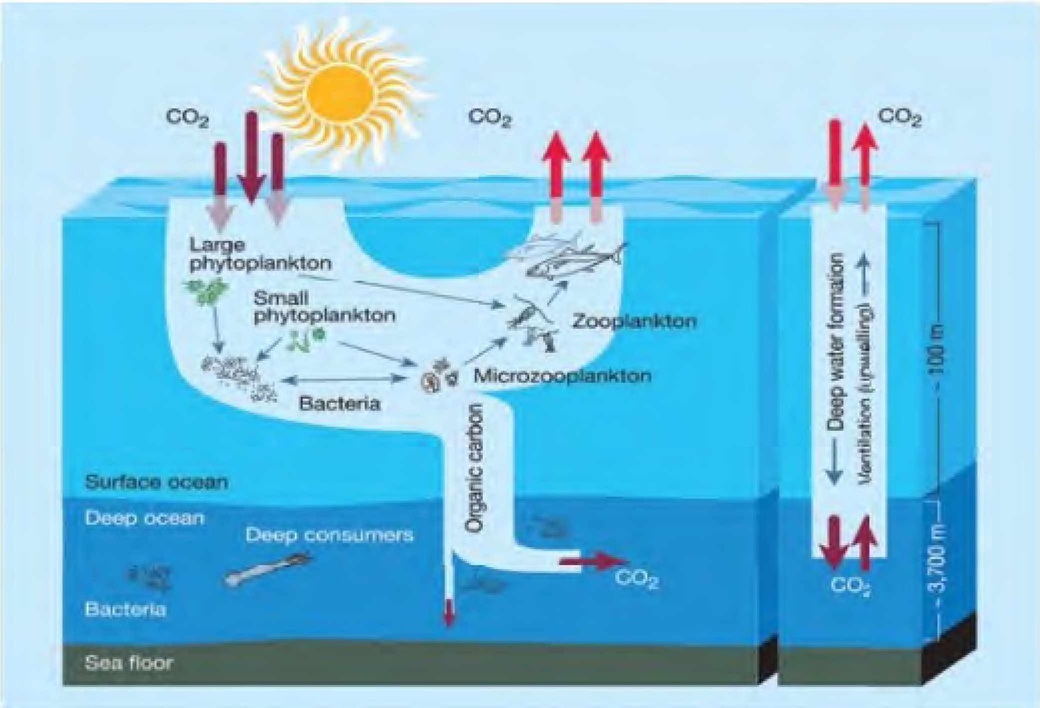


Figure 4.24 Solubility and Biological Pumps (credit Convention on Biological Diversity 2009, p.14 Figure modified from a graphic by Z. Johnson. credit Strong, Cullen and Chisholm, 2009, pp. 236-261[61])

Increased temperatures in West Antarctica (Vaughan *et al*., 2003) are likely to have resulted from large regional atmospheric warming as well as diminishing winter sea ice. Shepherd *et al*. (2004[62]) estimate that a 1°C increase in water temperature under an ice shelf increases the basal melt rate by about 10 m/year and could lead to ice shelf thinning and structural instability. Hansen (2007[63] n.p.) has suggested that: "increased rates of summer surface

[59] http://140.115.35.249/h/PGGM-new/latest_news/nature07716.pdf
[60] http://www.geos.ed.ac.uk/homes/wgeibert/GBC_Geibert2010_ForWebPage.pdf
[61] http://www.cbd.int/doc/publications/cbd-ts-45-en.pdf
[62]www.geo.utexas.edu/edu/courses/387H/PAPERS/Sheperd/Shepherd%20et%20al%20GRL%202004%20ASE.pdf
[63] http://www.ossfoundation.us/projects/environment/global-warming/sea-level-rise/slr-research-summary-2008/2007_Hansen.pdf see also Shepherd and Wingham (2007) http://www.sciencemag.org/content/315/5818/1529.abstract

melt in West Antarctica raises the danger that feedbacks among these climatic processes could lead to the nonlinear growth of ice discharge from the Antarctic".

The amount of ice melted in Antarctica during summer months has increased by 75% over the past 10 years. According to Alley *et al.* (2001 p. 3[64]): "[C]omplex interactions of the ocean with atmosphere, sea ice, ice shelves and the grounded ice sheet centred on West Antarctic continental shelves provide one of the two major sources of cold bottom water in the world's oceans".

This deep water link helps drive the global circulation of the oceans which, in turn, plays a major role in the world's climate system (Broeckern, 1994; Wong *et al*., 1990). According to Hansen (2007 n.p.[65]): "[W]arming of the ocean surface around Antarctica (Hansen *et al.,* 2006a) is small compared with the rest of world, consistent with climate model simulations (IPCC, 2007), but that limited warming is expected to increase".

4.5.2 Changes in Mass Balance in Antarctica

Recent events in the Antarctic Peninsula suggest that ice shelves are vulnerable to climatic change (Rott *et al*., 1996; Vaughan and Doake, 1996), because of several factors, including snow accumulation, loss of glacier ice mass, shrinkage of underlying rock and reductions in the extent of the ice shelves.

El Niño has strongly modulated snow accumulation in a sector of West Antarctica (120° W - 180° W, 75° S - 90° S) for the period 1980-1998 (Bromwich and Rogers, 1999). Research by Bromwich and Rogers (1999) has established that a strong correlation exists between the net flux of water on the Earth's surface and the Southern Oscillation Index. Ice shelves masses related to west Antarctic glaciers is decreasing by 95 Gt/year. Ice shelves masses related to east Antarctic glaciers are increasing by about 143 Gt/year (Bindschadler, 1998[66]).

[64] http://books.google.com.au/books?id=NnMkzzi2UmUC&printsec=frontcover&dq=The+west+Antarctic+ice+sheet:+behavior+and+environment&source=bl&ots=YhY0EJVKAF&sig=8YxjNh3P8WcKEX44i-RlGSogUrc&hl=en&ei=28oKTaiaIMf4rQeU6KTiCw&sa=X&oi=book_result&ct=result&resnum=3&ved=0CCwQ6AEwAg#v=onepage&q&f=false

[65] http://www.ossfoundation.us/projects/environment/global-warming/sea-level-rise/slr-research-summary-2008/2007_Hansen.pdf

[66] http://www.geo.utexas.edu/courses/387h/Lectures/Bindschadler_06.pdf, http://www.grida.no/climate/ipcc_tar/wg1/pdf/TAR-11.pdf, www.asoc.org/LinkClick.aspx?fileticket=v0ty7MxetG4%3D&tabid=36, http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch4s4-6-2-2.html

According to Bindschadler (1998), the rates of mass loss can be related to the potential for ice shelf instability. The West Antarctic Ice Sheet is a marine-based ice sheet; its edges lying below sea level flow into floating ice shelves. As explained by Anderson (1999) and Burroughs (2008[67] p. 2) the mass of the ice sheet has caused the underlying rock to shrink by between 0.5 and 1 km through a process known as by isostatic depression. Accelerated flow rates of West Antarctic glaciers seem mainly due to the decrease in ice shelves extent.

Collapsing of the West Antarctica ice shelves is caused by several factors such as basal lubrification and grounded ice thins, that will be discussed further. Bindschadler and Bentley (1997) note that for relatively thin ice with low surface slopes, as found in the West Antarctic ice sheets, the enhanced basal lubrification may be the most likely mechanism for enhancing ice discharge. When grounded ice thins, it drives the grounding line further inland. This positive feedback loop could cause complete ice sheet collapse (Weertman, 1974).

For basal lubrification, several hypotheses have been advanced. In the case of stabilising responses, ice stream is widening and the speed increasing. According to Alley *et al.* (2001[68] p. 7): "if the bed has numerous sticky spots or is a till whose strength permits only a slow increase of strain rate with increasing stress ... extra stress from ice stream widening may be transmitted to the ice stream bed".

If the ice begins to thin, colder ice will move nearer to the bed, which may begin to freeze, generating more sticky spots and producing stabilisation (Payne 1995; Engelhardt and Kamb, 1998, Anandakrishan *et al.*, 1999). On the other hand, Houghton *et al*., (1996 and 2001) suggest that enhanced velocity may trigger a string of positive feedbacks in which increased motion creates increased friction, generating more basal water, enhancing lubrification and increasing the motion of the ice sheet. Models developed to understand these complex dynamics commonly involve sophisticated solutions of heat and mass balance, often involving ice shelf physics needed to set parameters for surface mass balance ice shelf physics and parameterise surface mass balance.

Research conducted in the late 1980s suggested that the head region of Ice Stream B was thinning as the ice stream extended into inland ice (Shabtaie and Bentley, 1987; Shabtaie *et*

[67] ftp://140.208.31.106/pub/cml/ThesisNLB.pdf
[68] http://books.google.com.au/books?id=NnMkzzi2UmUC&printsec=frontcover&dq=The+west+Antarctic+ice+sheet:+behavior+and+environment&source=bl&ots=YhY0EJVKAF&sig=8YxjNh3P8WcKEX44i-RlGSogUrc&hl=en&ei=28oKTaiaIMf4rQeU6KTiCw&sa=X&oi=book_result&ct=result&resnum=3&ved=0CCwQ6AEwAg#v=onepage&q&f=false

al., 1988). According to the UNEP (2007), the Larsen B Ice Shelf sector average rate of melting more than doubled between 2004-2005 and 2005-2006. Scambos *et al*. (2003[69]) noted that in 2002, thinning of about 1 m/year of the ice shelf preceded the fragmentation of 3,300 km² of the Larsen B Ice Shelf in the West Antarctic Peninsula. Under specific conditions, shelves internal instabilities can amplify the ice thinning phenomenon as is the case for the thinning of ice stream B (Alley *et al*., 1994; Payne, 1995; Payne *et al*., 1997; Anandakrishan *et al*., 2003). If the ice shelf collapses, it cannot regulate the flow from the glaciers to the sea and the glaciers flowing into the ice shelf start moving with a higher speed. This was the case in 2002 after the break-up of the Larsen B ice shelf, when the speed of ice shelf movement became eight times greater than the speed which had been recorded prior to the fragmentation. The glacier surged ice was supported by the parts of the ice shelf undergoing widespread glacial retreat (Rignot *et al*., 2004; 2005 and 2008[70]; Scambos *et al*., 2004[71]; Cook *et al*., 2005).

According to Stammerjohn *et al.* (2008), in 2004 in the Antarctic Peninsula, the sea ice retreated 31 days earlier and advanced 54 days later than in 1979. The ice season extended by 85 days. Moreover, in the western Ross Sea region, the sea ice retreat occurred 29 days later and advanced 31 days earlier than in 1979; the ice season was extended by 60 days. Rood and Martens (2008) argued that the atmospheric conditions have a more visible influence on the sea ice advance than on the sea ice retreat, probably attributable to the circulation patterns, by free expansion to the Southern Ocean.

If this trend is confirmed in the Antarctic Peninsula, then the thinning of the West Antarctic ice sheet will probably continue, exacerbating sea level rise (Stammerjohn *et al.*, 2008). Furthermore, it is not clear that the bed of ice sheet B is presently warming over wide regions. Extreme contrasts and feedbacks play an important and complex role in the dynamics of the West Antarctic ice sheet; the collapse may be favoured by several factors and one of the most important could be internal ice sheet instability. According to NSICD (2004[72]) and Scambos *et al.* (2004 n.p.[73]) several ice shelves have collapsed since the 1980s, namely, Prince Gustav Channel, Larsen Inlet, Larsen A, Larsen B, Wordie, Muller and Jones.

[69] http://web.pdx.edu/~chulbe/science/reprints/ScambosHulbeFahne_ARS03.pdf
[70] http://www.nasa.gov/pdf/121652main_RignotetalGRLPeninsulaAccel.pdf, http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/40866/1/05-0586.pdf, http://www.phys.uu.nl/~broeke/home_files/MB_pubs_pdf/2008_Rignot_NatGeo.pdf
[71] www.vliz.be/imisdocs/publications/140205.pdf
[72] http://nsidc.org/news/press/20080325_Wilkins.html
[73] www.vliz.be/imisdocs/publications/140205.pdf

The Wilkins ice shelf had already lost 6% of its surface compared to a decade ago (Scambos, 2006). Recently a 570 km^2 ice island collapsed from the Wilkins ice shelf (Figure 4.25).

Figure 4.25 Wilkins 40 km Long Strip of Floating Ice Bridge Snaps (credit ESA[74] 2008 n.p.)

Anandakrishan and Alley (1997) studied the semidiurnal tidal cycles and noted that increased backpressure from the ocean slows the forward motion of grounded ice. Data from satellite measurements suggests that the stress state at the grounding zone would be more expanded if the Ross Ice Shelf were to be instantaneously removed (Jezek *et al*., 1985; MacAyeal *et al*., 1987). This suggests that the West Antarctic Ice Sheet will remain stable as long as the Ross Ice Shelf stays stable and is reinforced by local grounding.

Indeed, West Antarctica has proven to be one of the most complex and interesting regions on the globe for the dynamics of the ice sheet (Oppenheimer, 1998). Retreat of the West Antarctic ice sheet has been occurring since the 1950s and studied by Cook *et al*. (2005). Recent observations by the BAS have cast doubts on the stability of the West Antarctic Ice Sheet (Tirpak *et al*., 2005). The collapse of the West Antarctic Ice Sheet can be studied, as a model for the scientifically understanding of the phenomenon, despite a low probability of occurring during the next century (Vaughan and Sponge, 2002).

Regions adjacent to West Antarctica have differences in ice flow rates, despite similar gravitational driving stresses (Diersen *et al.*, 2002). Decadal regional changes observed

[74] www.eitb.com/.../89802/89802_antartida_mini.jpg

between 1900 and 2008 in both Arctic and Antarctic sea ice extents are shown in Figure 4.26.

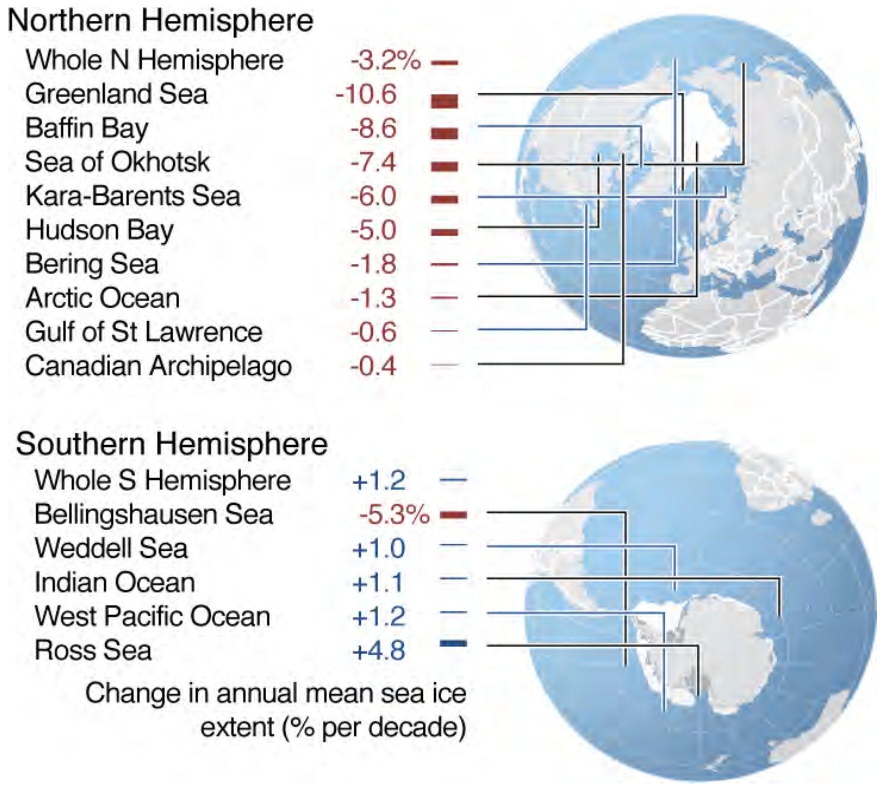


Figure 4.26 Regional Changes in Arctic and Antarctic Sea Ice Extents 1900 - 2008 (credit Ahlenius, UNEP/GRID-Arendal[75], 2007 n.p.)

However, many of these changes average out over larger areas. According to Allison *et al*. (2003 n.p.[76]) "[S]ea ice losses in West Antarctica over the past 30 years have been more than offset by increases in the Ross Sea region".

According to (Wingham *et al*., 2006 p.1627) "[M]ass gains from accumulating snow, particularly on the Antarctic Peninsula and within East Antarctica exceed the ice dynamic mass loss from West Antarctica". The West Antarctic ice sheet exhibits a more complex pattern of flow than its larger colder and slower neighbour, the East Antarctic ice sheet. The thinning of ice stream B is nearly balanced by the thickening of ice stream C (Shabtaie *et al*., 1988). In the coastal region, ice flow in the lower reaches of ice stream C stopped just over a century ago (Retzlaff and Bentley, 1993) but inland tributaries feeding the ice stream C

75 http://polynya.gsfc.nasa.gov/seaice_projects.html
76 http://www.news.com.au/antarctic-ice-is-growing-not-melting-away/story-0-1225700043191, ftp://ftp.soc.soton.ac.uk/pub/woceipo/SO/allison.pdf

remain active (Anandakrishan and Alley, 1997) forming an enlarging ice protuberance (Joughin *et al*., 1999). The differences in regional mass balance trends can be explained by the increasing snow accumulation in eastern Antarctica, or by the dynamics of ice and glaciers in West Antarctica (Davis *et al.*, 2005). The central East Antarctic Sheet is dry and cold. The main part of the sheet is stable and is not expected to melt considerably (Figure 4.27).

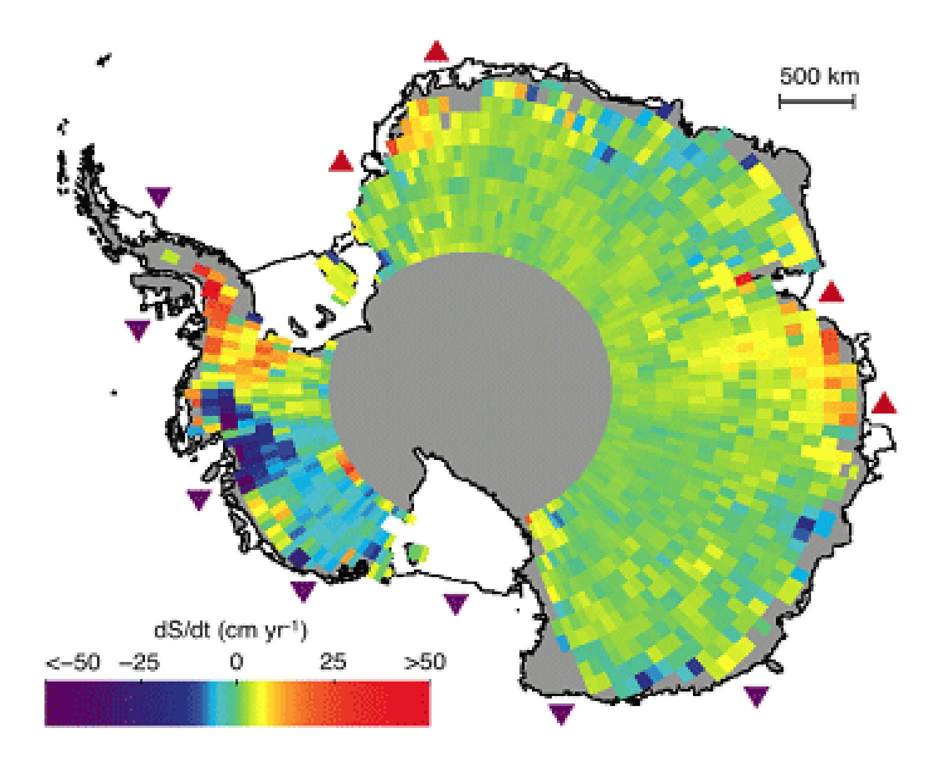


Figure 4.27 Changes in Mass Balance over the Antarctic Ice Sheet 1992-2003. Ice shelves are shown by red triangles and purple triangles (thickening thinning > 30 cm/year)
(credit Davis *et al.*,[77] 2005b p. 365, Steffen *et al.*, 2008 p. 49[78])

Figure 4.28 shows the thickening of the East Antarctic Ice Sheet while the West Antarctic Ice Sheet is thinning.

[77] www.ipcc.ch/.../ar4/wg1/en/fig/figure-4-19.jpeg www.ipcc.ch/.../ar4/wg1/en/ch4s4-6-2-2.html, http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter4.pdf
[78] http://downloads.climatescience.gov/sap/sap3-4/sap3-4-final-report-ch2.pdf

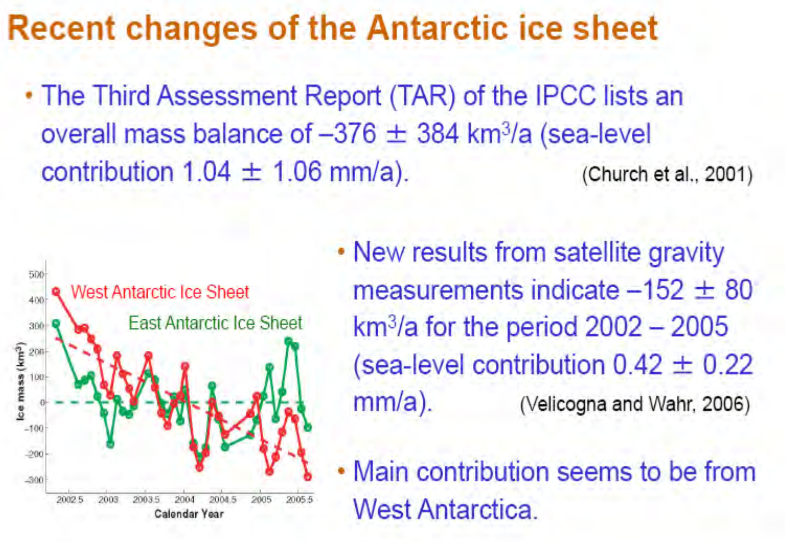


Figure 4.28 Recent Changes of the Antarctic Ice Sheet (credit Ohmura and Greve[79], 2008 p. 6)

Measurements of snowfall variability indicates that the best estimates of the overall mass trend is 27 ± 29 Gt/year, which would represent a large enough reduction in ocean mass of ocean mass to decrease global sea levels by 0.08 mm/year (Wingham *et al*., 2006). This range is negligible regarding the general sea-level rise scale. Wingham *et al*. (2006[80] p. 1634) noted:

> What is clear from the data is that fluctuations in some coastal regions reflect long-term losses of ice mass, whereas fluctuations elsewhere appear to be short term changes in snowfall. While the latter are bound to fluctuate about the long term mean accumulation rate, the former are not, and so the contribution of retreating glaciers will govern the 21st century mass balance of the Antarctic ice sheet.

NASA reported that in Antarctica a very slight increase (+1.2% per decade) was observed in the extent of annual mean sea ice over the period 1979 to 2005. However, the IPCC (2007) concluded that this increase of ice sheet mass was not significant and that there were no consistent trends either during periods of observation or between satellite observation locations. As noted by Huybrechts (2003) different types of numerical models have been applied to investigate the Antarctic ice sheet and to predict its current and future behaviour (Hulbe and Payne, 2001). There are indications that sea ice may be increasing more at the period of minimum coverage (March) than at the period of maximum sea ice extent in

[79] http://eprints.lib.hokudai.ac.jp/dspace/bitstream/2115/34393/6/Greve.pdf
[80] http://rsta.royalsocietypublishing.org/content/364/1844/1627.full.pdf+html see also http://www.cpom.org/research/djw-ptrsa364.pdf

September (IPCC, 2007[81]). For example, regional variations include an increase in the Ross Sea (+4.8% per decade) and a loss in the Bellingshausen Sea (-5.3% per decade). Wingham *et al*. (1998[82] p. 457) noted:

> The average elevation of the Antarctic Ice Sheet interior fell by 0.9 ±0.5 cm/year from 1992 to 1994. If the variability of snowfall observed in Antarctic ice cores is allowed for, the mass imbalance of the interior, this century, is only -0.06 ±0.08 of the mean mass accumulation rate.

The IPCC (2007) reported that during the years 1993 to 2003 the overall Antarctic Ice Sheet mass balance ranged from a growth of 50 Gt/year to shrinkages of 200 Gt/year. More specifically, since the 1990s, SAR techniques were used to study the AIS (Jacobs et al., 1992; Jezek, 1999). RADARSAT and Multiangle Imaging SpectroRadiometer (MISR) were used to demonstrate that the iceberg-calving cycle on the AIS is sensitive to seasonal changes in austral summer (December to March[83]) (Young & Hyland, 2002; Fricker et al. 2002, 2005). Ice, Cloud, and land Elevation Satellite (ICESat) was used to analyse the rift widening process with ice fragments, sea ice and wind-blown snow (Fricker, 2005). Temperatures were also analysed through the AMISOR project (Allison, 2001; Church *et al.*, 2002[84]). Ocean–atmospheric general circulation models simulating a warming of 3°C in the AIS region show that horizontal circulation of currents direction would change and that the melt rates from the base would increase substantially (Williams, Warner and Budd, 2002). The study found estimated that net mass loss of 14.2 Gt yr^{-1}, would increase by approximately 28.4 Gt yr^{-1}°C^{-1} suggesting that the mass loss rate is highly dependent of ice shelves ocean temperatures.

4.5.3 Sea Level Rise

Data compiled and aggregated by the IPCC on global sea level rise from 1880 to 2007 are presented in Figure 4.29. In 2000 a general tendency of sea level increasing (20 cm) has been observed compared to 1900.

[81] http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter4.pdf
[82] http://www.sciencemag.org/content/282/5388/456.abstract
[83] http://www.sciencedaily.com/releases/2005/06/050614002105.htm
[84] http://www.antarctica.gov.au/__data/assets/pdf_file/0009/21222/27_28_aam.pdf

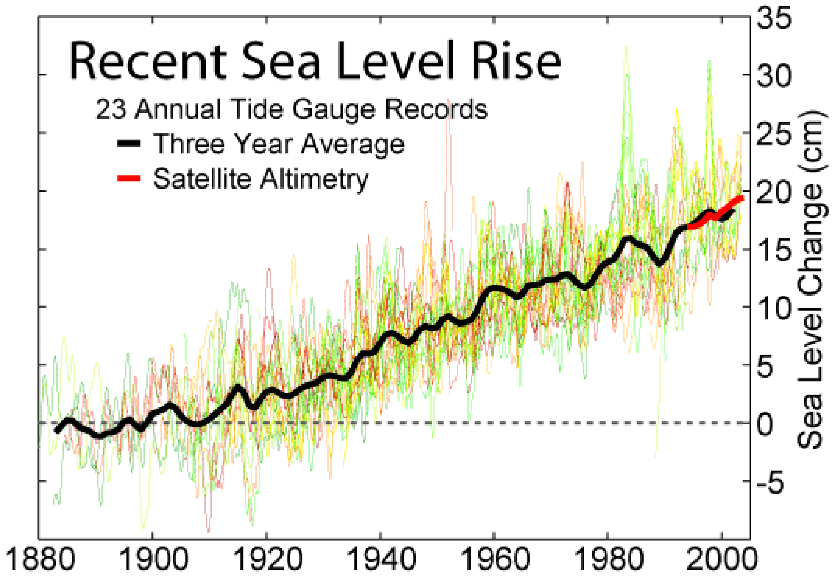


Figure 4.29 Global Sea Level Rise since 1880 to 2007 (credit IPCC[85], 2008 n.p.)

Sea levels change with time and space elements according to ocean mass depending on the temperatures of the ocean and related expansion and contraction processes (White, 2008). Sea level does not change uniformly. There can be large ocean regions with a decreasing sea level even when the overall global mean sea level is increasing. There are many processes that drive these changes. One of them is the exchange with ocean water of the water stored on land by glaciers and ice sheets. Ice shelves melting and mass loss does not affect sea levels because ice shelves are already floating. Indirectly the sea level is affected by the impact of ice shelves on the stream of glaciers. The ocean hydrostatic force affects the margins of the ice shelves by decreasing the ice shelves discharges (Dierssen, 2002). Sea level projections closer to and beyond 2100 are dependent on potential impacts of future greenhouse gas emissions, with both ocean thermal expansion and the ice sheets potentially melting. In addition, dynamic responses of the Greenland and West Antarctic Ice Sheets could lead to a more rapid rate of sea level rise than that from surface melting alone (Dieckmann and Hellmer, 2003). Present day contributions from Greenland come from both surface melting and iceberg calving, while for the Antarctic, they come more from iceberg calving. Computer model simulations of the potential collapse of the West Antarctic Ice Sheet have been conducted by Bindschadler and Bentley (1997), Bindschadler (1998), Bliesner *et al*. (2006) and Vaughan (2006[86]). Nasa (2006[87] n.p.) explained that Zwally *et al.*

[85] http://en.wikipedia.org/wiki/Current_sea_level_rise
[86] http://www.jstor.org/pss/4095837
[87] http://www.nasa.gov/vision/earth/environment/ice_sheets.html

(2005) reported that satellite surveys and mapping confirm that: “there was a net loss of ice from the combined polar ice sheets between 1992 and 2002 and a corresponding rise in sea level”. A collapse of the West Antarctic ice sheet is considered possible, if not highly likely, over the next few centuries, with a potential to raise global sea levels by approximately 5 m (Bindschadler, 1998). Still larger sea level rises are possible, if changes propagate into the East Antarctic ice sheet (Zwally *et al.*, 2005[88]). Simulation of the sea level increases in case of a total melting of the Antarctic and Greenland Ice Sheets is shown in Figure 4.30.

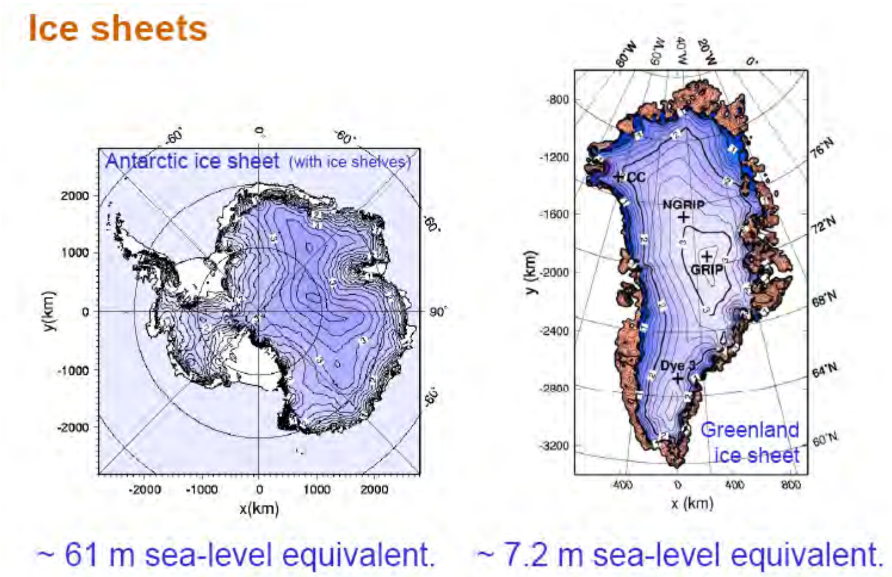


Figure 4.30 Simulation of the Behaviour of Antarctic and Greenland Ice Sheets (credit Ohmura and Greve[89], 2008 p. 3)

Oceanographic and meteorological impacts of vertical land movement increase the uncertainty about what might happen to relative sea levels at regional scales in the future (ASOC, 2010). The maximal average increase of the sea level on Earth is expected to be between 18 cm up to 1 m by the end of the 21st century (IPCC 2007, Australian Climate Institute ACI, 2007).

4.6 Discussion

This chapter had presented an assessment of the iceberg environment according to geophysical, ecological and climatic conditions and within a context related to climate change and global warming. Icebergs have important ecological roles. Icebergs have

[88] http://www.ingentaconnect.com/content/igsoc/jog/2005/00000051/00000175/art00001
[89] http://eprints.lib.hokudai.ac.jp/dspace/bitstream/2115/34393/6/Greve.pdf

impacts in Polar Regions and interact with the polar ecosystems as well as with climatic systems such as currents and winds. Icebergs are a perennial and natural source of disturbance of coastal ecosystems and a source of mineral and organic matter deposits when calving.

Large icebergs have been calved from Antarctic ice shelves more frequently in the three last decades in the warming context of West Antarctica (Kenneally and Hughes, 2006). Climate change affects the Antarctic Peninsula. Large calving events started in 1989 on the west side of the Antarctic Peninsula (Doake and Vaughan, 1991) with disintegration of the Wordie Ice Shelf, followed by the George VI Ice Shelf in 1995 and the Wilkins Ice Shelf in 1998 (Scambos *et al.*, 2000). In the east side of the Antarctic Peninsula, the Larsen Ice shelf started to disintegrate in 1995 (Rott *et al.*, 1996). The disintegration phenomena have been propagated in the Ronne Ice Shelf and the Filchner Ice Shelf in 2002. In the Ross Iceshelf in 2005 the calving of giant icebergs started in 1987 (Keys *et al.*, 1998) and culminated on 27 October 2005 with the calving of giant iceberg B15.

The current global climate change debate is contemplating changes in temperatures on a global scale and, in Antarctica, major changes in ice mass balances and potential rises in sea levels. Giant icebergs drifting in the Southern Ocean melt in the Circum Antarctic current, extracting heat and affecting the ecosystem.

Having in mind the aim of my thesis to transport one tabular iceberg from Antarctica to Australia, the use of icebergs may affect a number of ecosystems including Antarctica itself, transportation routes in the Southern Ocean and target destinations. In Antarctica, the impact is likely to be on the marine ecosystem and will reflect the particular transportation system employed. To eliminate the risk of transporting local marine fauna or flora (Jenior, 1978) on the benthic communities, zooplankton and phytoplankton in the vicinity of icebergs, iceberg capture should take place at least 200 miles offshore. As noted by Ryland (1997) at this distance the probability of disturbing marine populations is much reduced. In any case, the development of a new iceberg transportation project from the AAT to WA must give close consideration to interactions with the environment. In case of hypothetical large ice shelves calving, large iceberg transportation projects could help reducing the global impacts on sea levels and climate but this would need further investigation and complex studies. The thesis will now focus on the history of iceberg transportation.

Chapter 5 A History of Iceberg Transportation

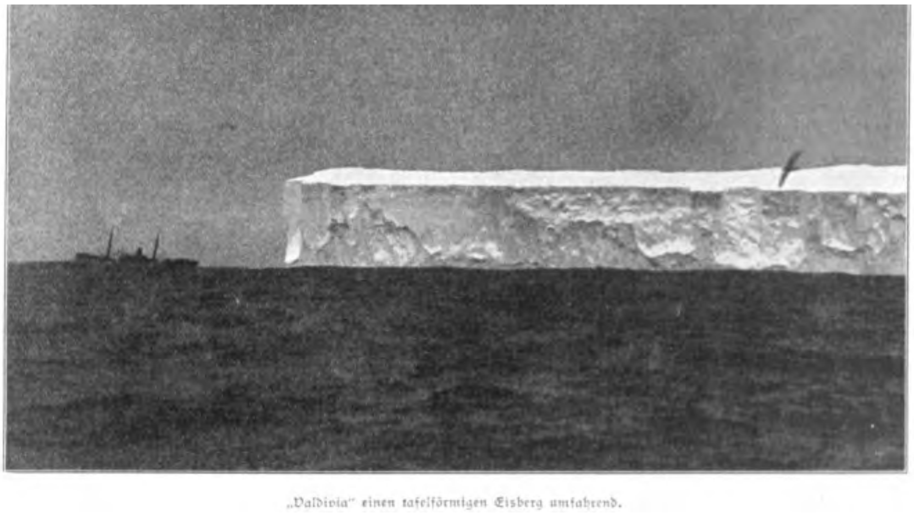


Figure 5.0a Tabular Antarctic Iceberg, December 7, 1898, 55°47' South, 29°32'East, (credit Chun, 1903 Iceberg seen on December 7, 1898. "In: "Aus den Tiefen des Weltmeeres" p. 219.The *Valdivia* tows a tabular iceberg at 55 47 South Latitude, 29 32 East Longitude. NOAA Photolibrary no 3573[1])

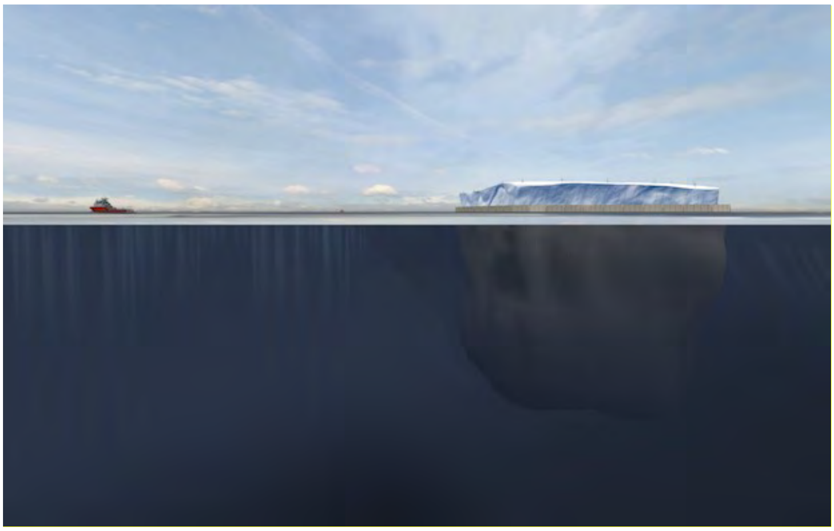


Figure 5.0b Iceberg Transportation Simulation (credit 3DS, 2010[2])

It is true that any energy source is transformable but the scientist is not surer to find in his researches something economically benefiting than the explorer to reach a fertile land.

(Translated from Weil, 1935 p. 27)

[1] http://www.photolib.noaa.gov/htmls/ship336l.htm

[2] http://perspectives.3ds.com/environment/how-to-tow-an-iceberg-pt-1/

Chapter 5 A History of Iceberg Transportation

Transportation geography studies the historical changes of transport networks engendered by transportation technologies, within a certain area and the technological, economic social and environmental conditions of transport systems (Rodrigue, 2009). The objective of this chapter is to critically analyse the scientific and technical literature of the last four decades on iceberg transportation. Historical examples of iceberg transportation operations are examined to investigate how far these projects went and the reasons why these projects failed. The idea of towing icebergs rose since 1890 and systematically dropped because of technological and financial institutional lacks. Three main periods are observed for icebergs freshwater transportation, during the 20^{th} century and at the beginning of 21^{st} century:

- the feasibility period, during the 1970s. Iceberg transportation projects were developed actively to estimate the feasibility of a large scale transportation process. Most of the projects were based on petrol based transportation systems;
- the technical period 1980s/1990s. Feasibility studies were more focused on transportation systems and transportation routes considered were shorter. Costs were still too high. Projects did not receive enough funding to be developed;
- the frozen period from the 2000s to present.

While previous attempts to move icebergs have met with many difficulties, collectively they provide a number of insights and innovations that may be applicable to future projects for a sustainable iceberg transportation system from Antarctica to West Australia.

5.1 Pioneering Achievements

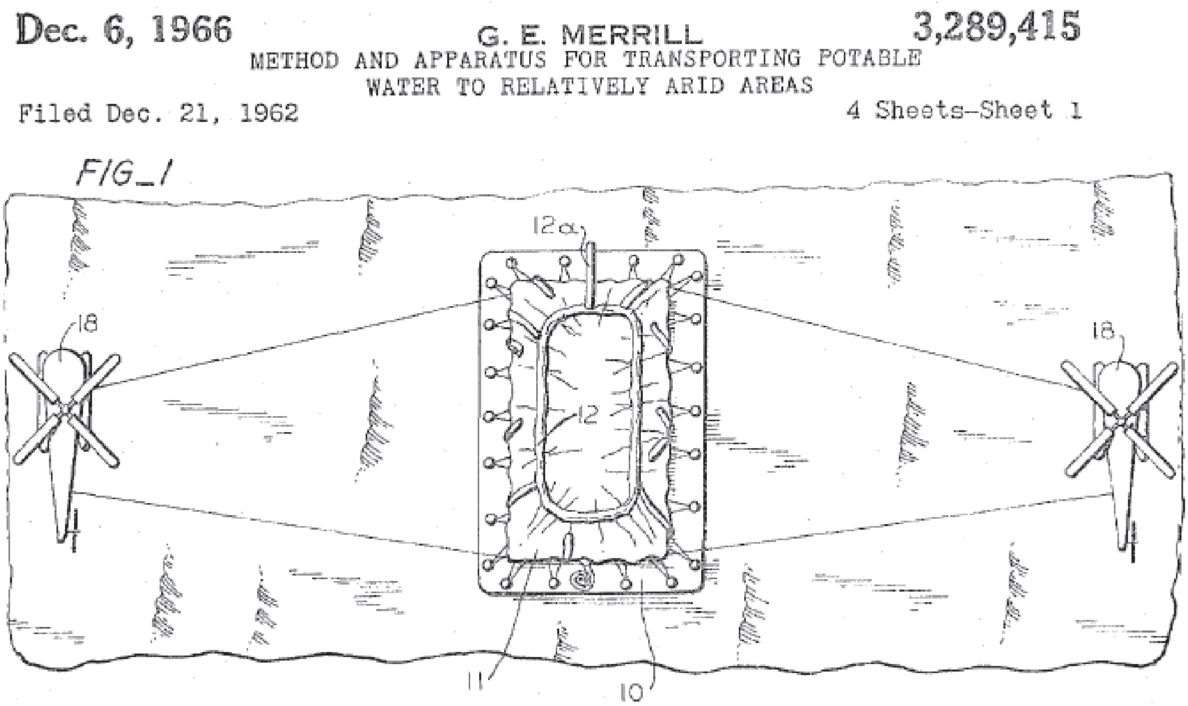
The idea of iceberg transportation is closely associated with the development of polar explorations. Since the middle of the 19^{th} century, polar exploration shipping has been the most practical means of attempting iceberg transportation. First iceberg transportation experiments are not well documented. James Cook crew of the boat *The Resolution* used an iceberg of 15 t as a source of fresh water in 1773 (Holmes, 1993[3]). First proper attempts of iceberg transportation started in the 1850s when 20 m long sailing boats were used to tow small icebergs over 4,000 km from Laguna San Rafael in Chile to Callao in Peru (Weeks,

[3] http://207.112.105.217/PEN/1993-06/holmes.html see also Beaglehole, 1974 pp. 361-363 http://www.nzetc.org/tm/scholarly/tei-Bea04Cook-t1-body-d20.html

1980). These icebergs were used to supply ice to the emerging ice market in Peru. A transportation process based on small barges carrying 5 million t icebergs was developed but was abandoned in the late 1890s because the ice often melted quickly and the operation was not economically competitive (Charlier, 1991).

In the late 1950s, the oceanographer Professor John Isaacs from the Scripps Institute US suggested that icebergs could be transported from the Arctic to Los Angeles, California (Burt, 1956a,b). Isaacs' proposal consisted of towing a tabular iceberg with a 3 million tonne tug boats, but this expensive plan was never carried out.

Later in the 1960s Merrill (1966) designed an innovative patent for iceberg transportation project (Figure 5.1 and Figure 5.2). This design inspired the work of Mougin and Sobinger in the 1980s.



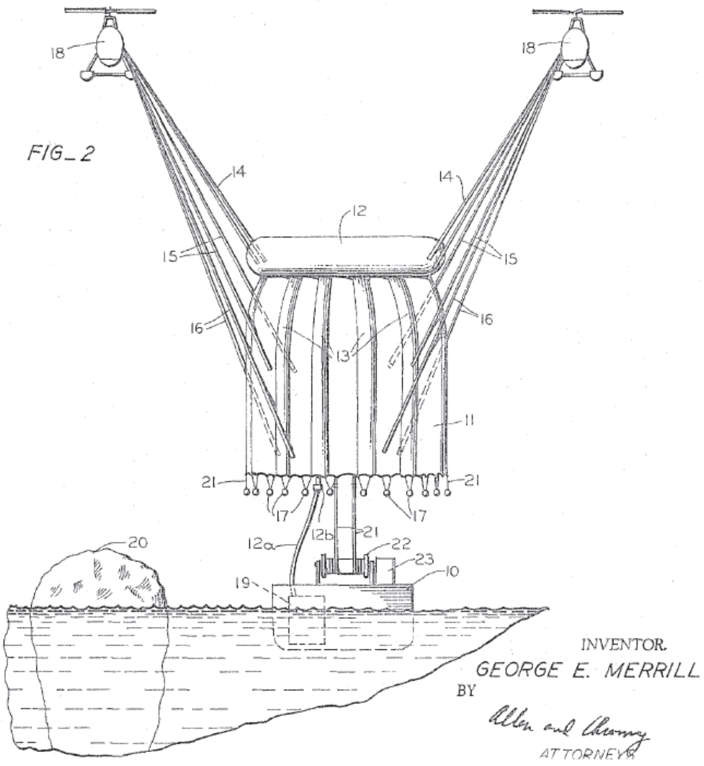


Figure 5.1 Method and Apparatus for Transporting Potable Water to Relatively Arid Areas (credit Merrill, 1966 p. 1[4])

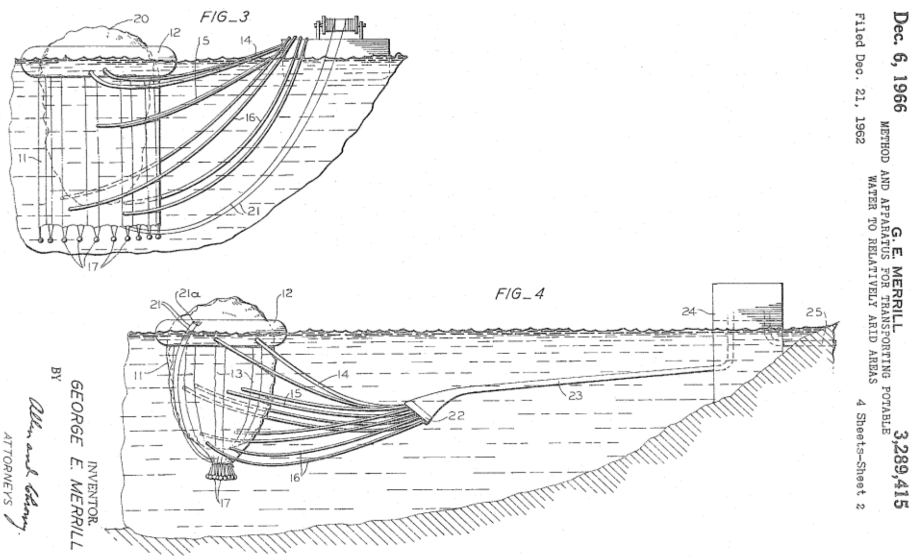


Figure 5.2 Method and Apparatus for Transporting Potable Water to Relatively Arid Areas (credit Merrill, 1966 p. 2[5])

[4] http://www.freepatentsonline.com/3289415.pdf
[5] http://www.freepatentsonline.com/3289415.pdf

This project was based on encapsulating in a case an iceberg towed to the coast of a relatively arid region. The melting water of the iceberg would have then be collected, processed and supplied to the coast.

In the 1970s the international context changed with the oil crisis. Meanwhile, in the 1970s an expansion of interest in new freshwater resources on a global scale reflected increasing population growth, and the growing financial power of nations rich in oil and poor in water, such as Saudi Arabia, which initiated and supported large projects that considered icebergs as a potential supply of freshwater. Crandell (1971) published a study on lahars impacts on underground waters underlying the possibilities for collecting melted freshwater from an iceberg under tow. Then, in the early 1970s Weeks and Campbell (1973) and Hult and Ostrander (1973) studied in detail iceberg towing. The first investigation of iceberg transportation to Australia was initiated by the Australian Academy of Science According to Schwerdtfeger (1981 p. 1): “[I]n 1974, the Australian Academy of Science formed a special committee to investigate the feasibility of icebergs being towed to southern Australia augmenting existing sources of freshwater supplies”.

5.2 First International Conference on Iceberg Utilisation

In the 1970s, the growing interest in iceberg transportation led to the first international conference on iceberg utilisation held at Iowa State University, Ames, Iowa from October 2-6, 1977. The proceedings of the conference were published by Pergamon, New York as *Iceberg Utilisation for Fresh Water Production, Weather Modification and Other Applications* (Husseiny, 1978; Balaban, 1979). The conference was a key event for the development of iceberg transportation technologies (Husseiny, 1978; Balaban, 1979). The conference drew attention to the potential of icebergs as a water and thermal energy resource. Speakers at the conference provided information and recommendations on the determination of the location, shape, characteristics and dimensions of icebergs for transportation. Delegates canvassed ideas associated with iceberg transportation including satellite technologies, radar, iceberg properties and behaviour, freshwater loss, geophysics, harnessing, towing, transportation reliability, safety, itineraries for transportation, sea and meteorological conditions and sailing plans. This conference was the first international recognition of icebergs transportation as an academic discipline and became the corner stone for future iceberg transportation research.

In the years immediately following this conference, scholars and academics commented on the feasibility of iceberg transportation, as described below. Weeks and Mellor (1978) argued that tabular icebergs were the most convenient to harvest, because their large, flat shape can prevent rolling induced by waves and transportation. Tabular icebergs are more commonly calved from the Antarctic ice shelves. In the Arctic regions tabular icebergs are rarer and smaller. In the Arctic, Kovacs (1977) reported iceberg thicknesses varying between 25 m and 70 m. The variability of the size of tabular icebergs in Antarctica was analysed and discussed by David (1978). He argued that 20% of the tabular icebergs in Antarctica have a length between 1 and 3 km and the optimum transportation size, in terms of logistical feasibility, was between 0.04 - 0.05 km^3, corresponding to 400 m long, 600 m large and 150 m deep (David, 1978). He suggested the economical optimum size was 1.5 km long, 350 m wide and 250 m thick, representing a volume of about 0.12 km^3. Data on the thickness (between 30 m and 280 m) of icebergs was also reported by Swithinbank (1977).

From these studies it was suggested that Antarctica was the ideal region to operate icebergs. Two specific harvesting sites were targeted: the Amery Ice Shelf and the Ross Ice Shelf. The Amery Ice Shelf was seen as a supply for Australia, and the Ross Ice Shelf for South America for the western hemisphere (Kelley, 1978). Burrows (1976) argued that the Amery and Ross Ice Shelves were ideal source locations for an iceberg transportation project from the AAT to Australia.

Remote sensing techniques (radar, SAR - Synthetic Aperture Radar and satellites) to detect and locate icebergs were proposed by different authors (Brodsky, 1978; Kovacs, 1978; Moore, 1978; Swithenbank, 1978; Campbell *et al.*, 1980; Orheim, 1980) as a useful technology for tracking icebergs. Since the 1970s the development of satellite-based global positioning technologies has meant the distribution of icebergs can be monitored precisely in real time. Satellite images can be used to select accessible areas in which icebergs having appropriate characteristics for transportation can be identified and chosen. The first Canadian project (Iceberg dynamics Project 1971 Fenco, see also NFLD, Ltd, PERD Database- Shape Database Report no. R21) was related to towing icebergs southward, to protect maritime routes and oil and gas offshore facilities.

In the late 1970s there was unprecedented interest and enthusiasm for studies which examined technical aspects of harnessing icebergs, determined by the development of gas and oil offshore industry in North Canada. Studies by Huppert and Turner (1978), Cluff (1979), Robe (1979), Russell (1979) and Smith (1979) investigated the deterioration properties of icebergs. Frisch and Kresta (1979), Humphry (1979), Hussain (1979) and Mougin (1978) examined techniques and technologies for 'bagging' icebergs. Mellor (1978) and Chirive and Miller (1978) conducted empirical investigations on the movement of icebergs, while Denner (1978) examined the environmental impacts of iceberg transportation and Murphy (1979) and Mauviel (1980[6]) modelled various aspects of iceberg dynamics. Both De Marle (1978; 1980[7]) and Roberts (1978) looked at the possibility of using icebergs for power generation. Additional expertise and knowledge about iceberg transportation was also inspired by the practical considerations of the CIS - Canadian Ice Service Canada, which, since the 1970s, had developed a range of complex techniques for diverting icebergs that threaten oil platforms along the Canadian coast. Successful iceberg towing was performed from the 1970s.

In the vast majority of iceberg transportation projects tugboats have been proposed as a means to control and move icebergs. Tugboats generally range in size from 600 hp to over 10,000 hp, however larger tugboats can have power ratings up to 25,000 hp (20,000 kW) (Chirivella and Miller, 1978). The length of a tugboat varies between 10 and 70 m, and the width varies from 7 to 20 m. Technical details of a tugboat and an example of a working tugboat are provided in Figures 5.3 and 5.4.

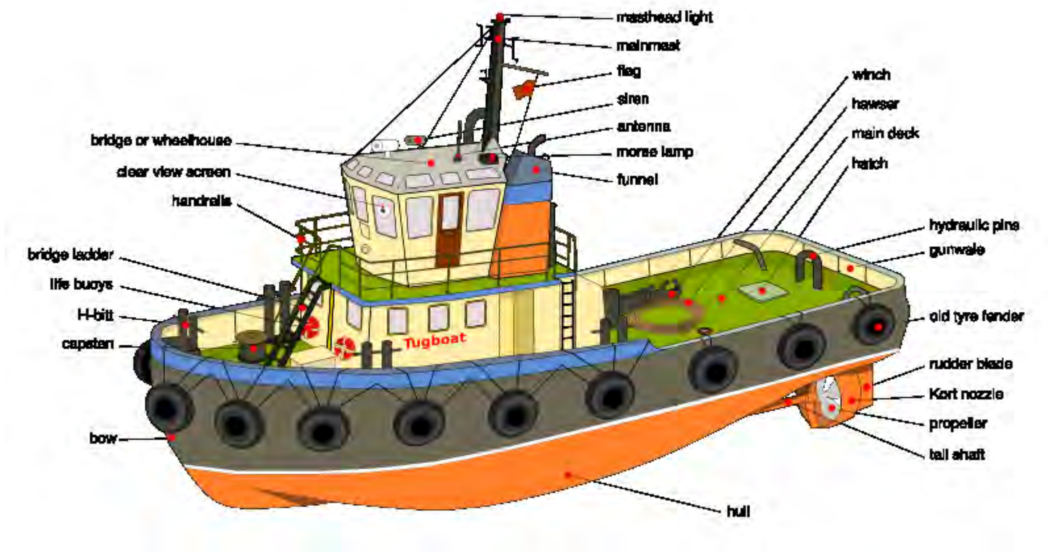


Figure 5.3 Schematic Representation of a Tugboat (credit Dahl[8], 2007 n.p.)

[6] http://www.igsoc.org/annals.old/1/igs_annals_vol01_year1980_pg123-127.pdf
[7] http://www.igsoc.org/annals/1/igs_annals_vol01_year1980_pg129-133.pdf
[8] http://en.wikipedia.org/wiki/File:Tugboat_diagram-en_edit1a.svg#globalusage

Figure 5.4 A Working Tugboat on Sea Propeller (credit Schneider[9], 2007 n.p.)

Ocean going tugboats are classified such as conventional, notch, articulated, and integrated according to how a tug boat interacts with other water craft. Monfort and Oudendijk (1979) have reviewed different technical solutions for towing (Figure 5.5).

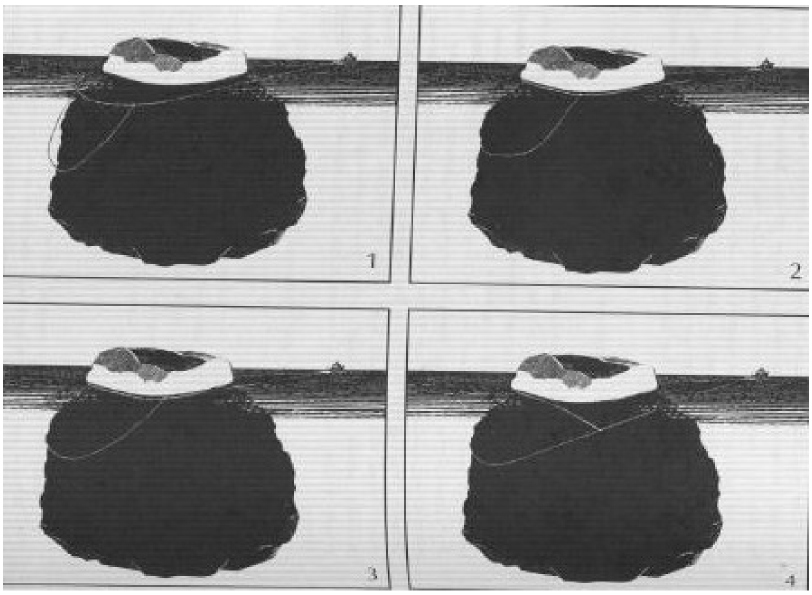


Figure 5.5 Iceberg Prepared for Towing (credit Husseiny, 1978 Bowring *et al.*, 2010[10] n.p.)

[9] http://en.wikipedia.org/wiki/File:VSPBoxer.jpg
[10] http://web.mit.edu/12.000/www/m2012/finalwebsite/solution/glaciers.shtml

Several tugs would be needed to transport an iceberg, increasing considerably the transportation costs. According to Weeks (1980[11], p. 4):

> As tug size increases, the thrust/power ratio invariably decreases, giving a supertug less than half the efficiency of small tugs. The simplest solution to this problem would be to use multiple small tugs to start a tow, decreasing their number as the tow proceeds... This procedure would also help resolve another problem: that the safe working load of the largest available wire rope is 3 times less than the force required to move a useful sized Antarctic iceberg.

In iceberg transportation, human safety is a major consideration. Tugboats must provide good living conditions, work facilities, food, and communication facilities for the staff.

Other propulsion systems have been studied such as a paddle-wheel system (El-Faisal, 1978). Paddle-wheel systems consist in automatic paddles using hydrodynamic drag and velocity. However paddle-wheel systems were not designed to operate in open seas and it is not clear if the 13 MW maximal power obtained by the system is achievable (Figure 5.6, Figure 5.7 and Figure 5.8).

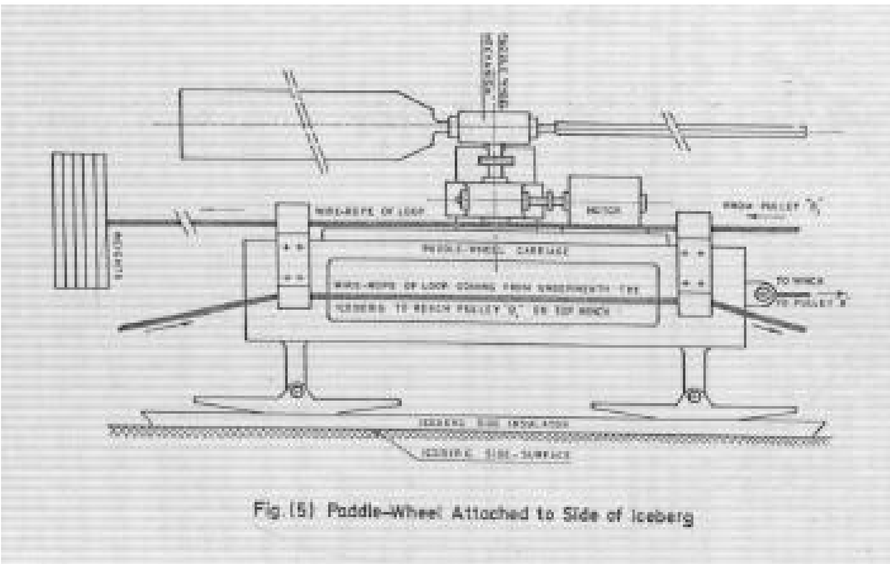


Fig. (5) Paddle-Wheel Attached to Side of Iceberg

Figure 5.6 Paddle-Wheel Attached to Side of Iceberg (credit Husseiny, 1978 in Bowring *et al.*, 2010[12] n.p.)

[11]http://web.mit.edu/12.000/www/m2012/finalwebsite/solution/glaciers.shtml
[12]http://web.mit.edu/12.000/www/m2012/finalwebsite/solution/glaciers.shtml

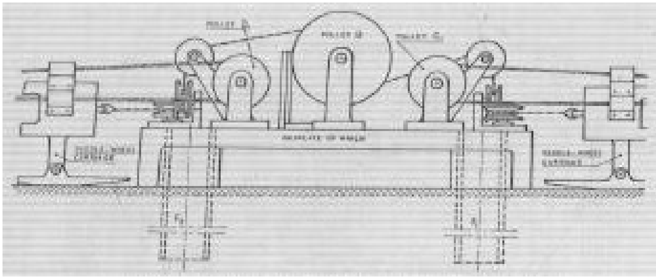


Figure 5.7.Paddle-Wheel Side View with Lifting and Lowering Winch (credit Husseiny, 1978 in Bowring *et al.*, 2010[13] n.p.)

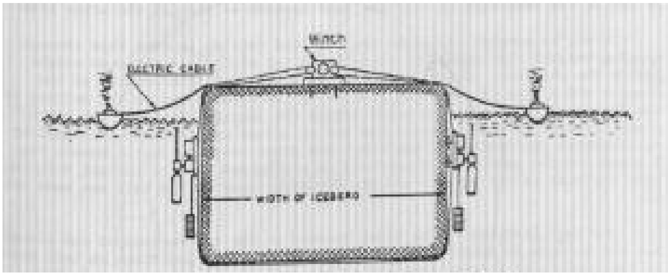


Figure 5.8.Paddle-Wheel Configuration (credit Husseiny, 1978 in *Bowring et al.*, 2010[14] n.p.)

Another study consisted in using solar energy form osmotic pressure from seawater and melting iceberg water (Davis, 1978; See also Figure 5.9).

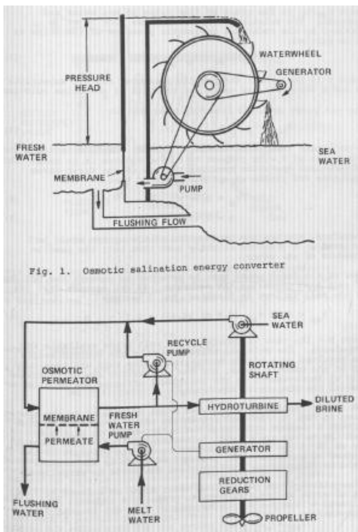


Figure 5.9 Osmotic Propulsion System Pump (credit Husseiny, 1978 in Bowring *et al.*, 2010[15] n.p.)

[13]http://web.mit.edu/12.000/www/m2012/finalwebsite/solution/glaciers.shtml
[14]http://web.mit.edu/12.000/www/m2012/finalwebsite/solution/glaciers.shtml

Another alternative option considered was to use the natural migration of icebergs (Fuchs, 1978). Transportation systems were designed to self-propel icebergs with OTEC Ocean Thermal Energy Conversion systems and thermodynamic energies of the differential between sea water temperature and ice temperature. Propulsion plans between 2 and 10 million newtons and 7 and 30 MW were designed. 60 GW are required to propel a tabular iceberg. The thermodynamic fluid cycle relying on the use of large amounts of ammonia or propane, the process would be associated with high pollution risks in case of capsizing (Figure 5.10).

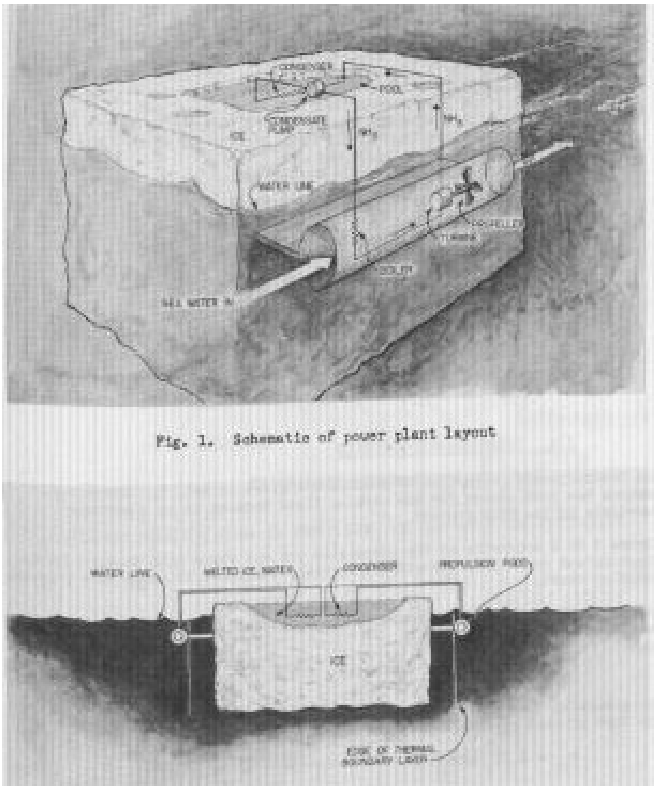


Figure 5.10 Iceberg Self Propulsion System: Installation of a Self Power-Plant with Propulsion rods and Otec Condenser in Iceberg (credit Husseiny, 1978 in Bowring *et al.*, 2010[16] n.p.)

De Marle (1978) and Roberts (1978) studied the potential to produce fresh water and also to produce energy from icebergs. They noted that a large amount of energy could be obtained through the thermal gradient if the icebergs are transported to lower latitudes (50° S). The power plant developed by the Automotive and Aerospace American Corporation - TRW Inc. is shown in Figure 5.11.

[15] http://web.mit.edu/12.000/www/m2012/finalwebsite/solution/glaciers.shtml
[16] http://web.mit.edu/12.000/www/m2012/finalwebsite/solution/glaciers.shtml

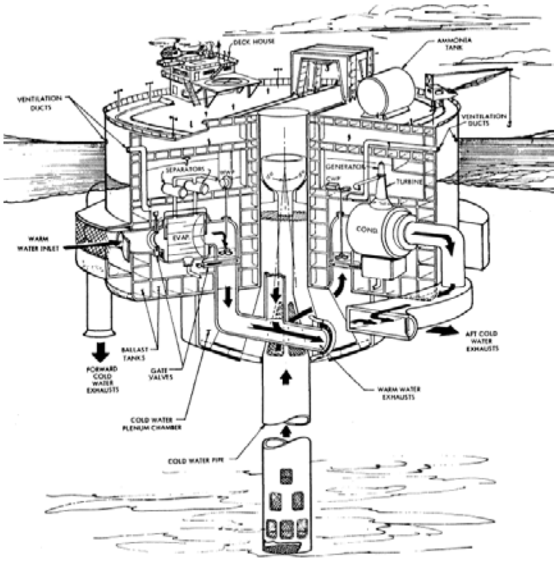


Figure 5.11 Concept of a 100 MW, OTEC Power Plant. One of the four 25 MW power modules. Platform diameter 100 m. TRW Systems Group, Inc. 1975 (credit Cohen, 1982 p. 149)

Iceberg melting was studied. Average melting rates as high as 0.116 m/day were calculated (Frisch and Kresta, 1978; Hult and Ostrander, 1978). Techniques to envelop the icebergs were also proposed (Hult and Ostrander, 1973[17]; Frisch and Kresta, 1978; Mougin, 1978). An envelope in polyurethane was chosen because of its insulating properties. For the deployment of this envelope, a process based on the spraying of a foam material to wrap the iceberg was proposed (Hult and Ostrander, 1973; Mougin, 1978, see also patent p. 176).

5.3 Feasibility Studies during the 1970s

The most significant studies into the feasibility of iceberg transportation undertaken in the 1970s are described below. As mentioned by Burt (1956a and 1956b) the first Scripps Insitute Corporation proposal by John Isaac did not obtain enough financial support and was not successful. Weeks (from the CCRL) and Campbell (from the USGS) (1973[18]) decided to review Isaac's project and designed a transportation project to tow a 120 m by 85 m iceberg. It consisted in towing "an individual unprotected iceberg to the most easily reached destinations, such as Australia" (Weeks, 1980[19] p. 1).

[17] http://www.rand.org/pubs/reports/2008/R1255.pdf
[18] http://journals.cambridge.org/action/displayAbstract?fromPage=online&aid=5656788
[19] http://www.igsoc.org/annals/1/igs_annals_vol01_year1980_pg5-10.pdf

5.3.1 RAND Corporation Proposal

Later in the 1970s, two scientists at the RAND Corporation, Later Hult and Ostrander (1973), supported by the National Science Foundation, continued their work and designed a towing system for iceberg transportation of a 3 km long and 300 m deep iceberg with insulation equipments and train systems. In 1978, the California State Senate engaged the RAND Corporation to tow icebergs from Antarctica to provide freshwater to California. Hult and Ostrander (1979) noted that during an 8,000 km iceberg tow and before reaching tropical waters, up to 1,300 m of its thickness would melt. This represented an average melting rate of 2 m/day. Their calculations showed that the project was not economically feasible as the icebergs melted too much, resulting in loss of 80% of the iceberg volume. The operation was also deemed to be technically too risky, especially considering the extreme meteorological conditions (winds, waves, precipitations) that persist in the Southern Ocean and the physical manipulations required at destination. To improve towing capacity and decrease towing time, they proposed the use of a ship powered by nuclear generators to tow trains of icebergs. These ideas of an ‘iceberg trains', comprising icebergs linked together, driven by electric propellers and powered by a floating nuclear plant were studied by Grossman (1978) and later studied by Redmond and Tharp (1993) (Figure 5.12).

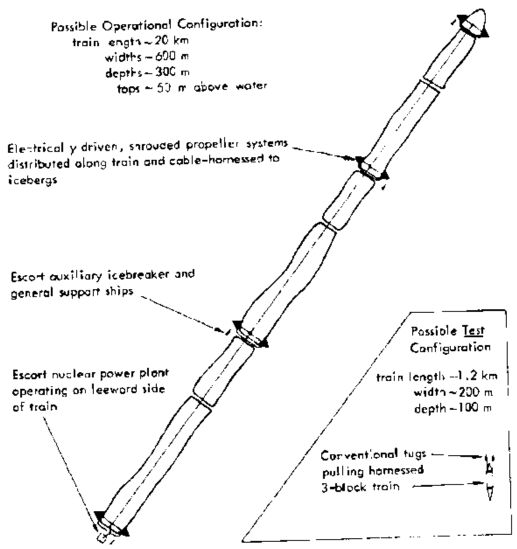


Figure 5.12 Illustrations of a Train of Icebergs (credit Hult and Ostrander, 1978[20] p. VIII)

[20]http://www.rand.org/pubs/reports/2008/R1255.pdf

5.3.2 Saudi Arabia Project

In the late 1970s, the Saudi Arabian Prince Al-Faisal commissioned the French explorer Victor and the American RAND Corporation to tow an iceberg from Antarctica to Jeddah, Saudi Arabia. It was proposed that the operation would use four tugs, and the iceberg would be covered by a plastic envelope in order to limit melting (Victor, 1979). The main advantage of iceberg transportation for freshwater was that it was expected to be cheaper in terms of infrastructure costs than desalination plants. Victor (1979 and 1986[21]) concluded that a tabular iceberg would be suitable for transportation and he estimated that icebergs of around 150 million t, or about 1,200 m long, 350 m wide and 350 m thick, would start to make a towing transportation system profitable. Profits were roughly estimated as the difference between the price of water supplied and the energy costs for transportation. The predicted transportation cost was around US$50 million. The estimated price of freshwater was around 0.40 US$/t, 50% less than the price for the same quantity of freshwater obtained from desalination. Victor estimated that more than 10,000 icebergs of this size (1200 x 350 x 350 m) melted away every year in the Southern Ocean. He determined that the optimum size of iceberg for transportation would be 50 km long, 350 m wide and 350 m thick, corresponding to a volume of 7 km^3. This volume of ice represented the freshwater consumption of Saudi Arabia for several years, and would be likely to yield a profit of US$3 billion. Owen and Griffin (1977[22]) estimated the loss of water from the iceberg to be 2.25 m/day in 10°C seawater and a temperature gradient of 17°C in the case of tabular iceberg transported between Antarctica and Saudi Arabia. Victor estimated that towing operations from Antarctica to the Arabian Peninsula could be performed by wrapping the iceberg in sailcloth to slow its melting, and by using powerful tugboats to drag the iceberg. Utilising existing technical skills and with the assistance of a large monetary investment, Victor claimed that the company 'Icebergs Transport International' (founded by Prince Faisal) would be able to undertake the proposed operations. The forecast towing speed was about 1 knot (2 km/h) for a distance of 4,700 km. It was argued that the trip would take 10 months.

Victor (1979) also noted that a slight modification of the local micro-climate at the destination in Saudi Arabia could be expected because of iceberg melted water, but he didn't take into account the environmental impact of this melted water on the ocean, probably because the quantity of melted water from only one iceberg was thought to be too small to have an

[21] http://findarticles.com/p/articles/mi_m1310/is_1986_May-June/ai_4375017/
[22] http://dx.doi.org/10.1115/1.3450058 see also (Russell-Head, 1980; Hamley and Budd, 1986)

ecological impact. Small scale experiments were carried out (Mauviel, 1980[23]; Appendix 6). Experimental natural drift tests were carried out by Mauviel for Iceberg Transport International Ltd. in 1979 to determine the effect on drag of small variations in the shape of tabular icebergs. It was shown that Arctic icebergs constitute suitable 1 :10 scale models of Antarctic icebergs and that towing experience in the Grand Banks can provide useful information. The effects of various environmental conditions were studied as well as the drag coefficients for various model shapes with or without insulation skirts, the effects of added mass, the rotation of the models, and the steering possibilities on two models:

- a 1:100 model icebergs on Brienzer See, Switzerland where current velocity varies between 30 and 50 mm/s, and corresponds to the reduced current of the Southern Ocean. The model was built on site, as a 10 m by 5 m by 2.5 m wooden pontoon with a draught of 2.10 m kept at this depth by polystyrene foam blocks. Several drift tracks and velocity measurements were recorded with a net of buoys for reference. Mauviel calculated that for a tabular iceberg of 1,000 m by 500 m 250 m thick a tow force of 950,000 pounds was necessary for a speed of 0.5 knot in calm conditions. The tow force could be reduced to 630,000 pounds for a lozenge-shaped iceberg. With an angle of 0° between the iceberg axis and the iceberg track energy savings were optimal however the instability of the iceberg increased. The average natural rotation velocity of a 1,000 m long tabular iceberg was equal to 15°/h. A 20 pounds towing force would be sustain the same rotation velocity. This result indicates that iceberg steering could be carried out using a source of low power.
- a 1:60 19 m by 9 m by 4 m steel model chamfered at the corners was used in 700 m by 200 m by 7 m St. Malo harbour, France. The model corresponded to a 1,140 m by 540 m by 240 m thick iceberg. The model could be ballasted to desired draught. The tests consisted of towing the model, equipped with various measuring devices in order to determine the relationship between the drag forces and the towing speed. These two parameters were measured by first towing the model with a rope with an embedded dynamometer to measure the towing force and a protractor to calculate the orientation of the model compared with the rope. Fifteen hydrodynamical drag tests and drift monitoring during the, the sail tests were undertaken at different towing forces and orientations. With lateral skirts overlapping the model by 1.5 m reducing the frictional drag, drag was lower. The form drag coefficient represents the main part of the hydrodynamic drag of the iceberg. The form drag coefficient for the bow part was 63% higher than for the uncovered model. For a short transfer an iceberg with a draught high enough to reduce the ratio of drag: ice mass and not equipped

[23] http://www.igsoc.org/annals.old/1/igs_annals_vol01_year1980_pg123-127.pdf

with a frontal skirt should be chosen. Acceleration tests were performed at different flow angles and showed that the added mass of water is a linear function of the orientation of the drag force.

The movement of the models followed the wind direction (the main axis of the models staying perpendicular to the wind vector). The models had the same trajectories as fullscale icebergs. Sail propulsion was tested. Five panels made of sail cloth were arranged on the model; their total area was 22 m^2 which corresponded to 80 000 m^2 at full-scale. The model heading relative to the wind direction was self-controlled through a simple system. Drifting rods of 4 m length, ballasted at the same draught as the model, were set around the model; their drift tracks constituted a reference as they were supposed to integrate the variations of the wind action. Tests showed a significant deflection of 10° between the model drift and the reference frame of the rods. The orientation control unit functioned well, maintaining the sail profiles at an incidence of 300° to the wind direction. It was also found out that lateral insulating skirts improve the dynamic performance of a protected iceberg, whereas a bow skirt has a bad influence on the total drag.

The Saudi Arabia project experimental transportation was not successful (Victor, 1979). Weeks (1979) argued that crossing the equator the iceberg would quickly melt and despite the thermal insulation around the iceberg, most of the water would be lost. During the feasibility studies a series of other technical problems arose: the iceberg proved to be highly unstable during transportation; there was a lack of appropriate infrastructure at the arrival port; and the refuelling of tug boat vessels at sea by a 50,000 t tanker was fraught with difficulties. A 15,000 hp tug boat with a fuel storage tank of 1,000 t required 30 to 35 t of fuel a day. The two tugs used for the voyage would have needed 15,000 t of fuel, each, making the total fuel cost of the trip around US$5 million. Another obstacle the project had to negotiate was to navigate across the Gulf of Aden, which was not deep enough for the iceberg. One proposed solution to this problem was to cut the iceberg into smaller pieces. Slicing thick ice had been undertaken by previous polar expeditions as reported by CICERO Company (1975). However, no effective techniques for cutting or processing huge blocks of ice emerged at that time. The use of explosives to trim and shape icebergs was studied by Mellor (1982; 1985) and he noted that this technique was not effective. Page (1985) studied later similar techniques (Figure 5.13).

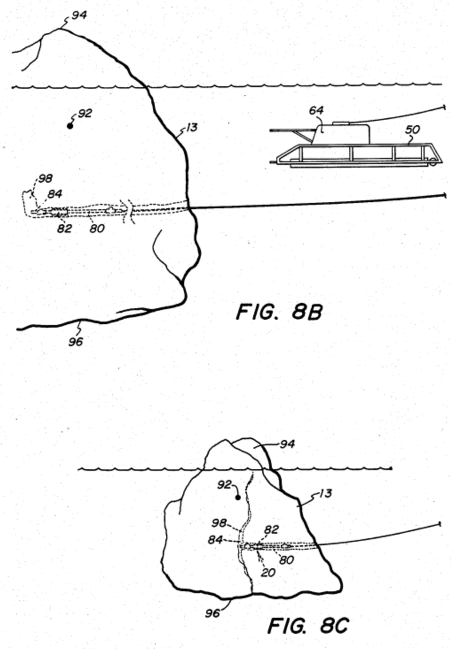


Figure 5.13 Fracturing Icebergs (credit Page[24], 1987 p. 7). Numbers refer to the patent description

During the 1980s in Saudi Arabia, desalination technology came to be considered as more reliable than iceberg transportation for generating freshwater, and a better long-term investment. Interest in desalination technology also grew elsewhere. Desalination technologies benefited from increased investment, around the world during the 1980s. However, the maintenance costs and the negative externalities from pollution which result from desalination plants were underestimated at the time and have been only recently more widely appreciated (See special issue of *Desalination*, 2003 vol 157, no 1 - 3).

5.3.3 Early Australian Projects

In the Southern Hemisphere during the 1970s, the Australian Antarctic Division (AAD) was playing a significant role in detecting icebergs. The first Australian remote sensing papers on icebergs were published by scientists working at the AAD (AAD, 2008[25]). The first Australian iceberg transportation research was reported by Job (1978a[26], 1978b, 1978c) and was related to the grounding of an iceberg on the continental shelf, offshore the mouth of Murray Darling River. Job "took a large number of factors into consideration" (Weeks, 1980 p. 4). A site was selected just north of Carnarvon in WA because of its depth by Warner (ERA, 1980;

[24] http://www.freepatentsonline.com/4640552.html
[25] http://www.antarctica.gov.au/__data/assets/pdf_file/0013/21064/ml_39573613275463_200805-antarctic-climate-science-report.pdf
[26] http://www.igsoc.org/journal/20/84/igs_journal_vol20_issue084_pg533-542.pdf

see also Day, 1980 p.31) and also in South Australia because of the depth of the shelf off the coasts while Crandell studied underground water recharges (Day, 1980 p. 32). Budd *et al*. (1980) and Hamley and Budd (1986[27]) studied the melting process of icebergs and suggested that Western Australia aquifers could be 'charged' with iceberg melted water instead of creating surface reservoirs and distribution systems with their related expense and evaporation problems.

The AAD noted (Parliament of Australia, 1984 p. 3): "Antarctic ice has the potential to supply not only Australia, but such water poor regions as Northern Africa and the Middle East". The projects developed in the 1970s and described in this section and their key characteristics are presented in Table 5.1. It can be noted that the estimated cost of freshwater was between 0.1 and 0.4 US$/m^3 0.5 and 1.6 US$/m^3 (in 1970 and 2010 values).

Table 5.1 Key Characteristics of Iceberg Transportation Projects in the 1970s

	Projects submitted by:		
Parameters	**Victor**	**Hult &Ostrander**	**Others**
Location	Antarctica - Saudi Arabia	Antarctica - California	Antarctica - Australia/Arctic - North America
Transportation Duration	6 months / 1 year	3 months/1 year	3 months
Iceberg volume	0.06 km^3 to 4 km^3	0.5 km^3 to 20 km^3	0.005 km^3 to 1 km^3
Project Cost	Up to US$100 million	US$200 million	Around US$15 million
Price (US$/m^{3}water)	0.5 US$/m^3	1 US$/m^3	around 1.5 US$/m^3
Propulsion	10^7 W	1.56 10^8 W	10^7 W
Advantages	No pollution, climatic engineering	Costs and Quantities	Human Scale
Improvements expected	Satellite Operating	Nuclear Propulsion	Plastic sheets, power plants, detection

5.4 Projects and Studies in the 1980s

In the early 1980s Schwerdtfeger (1982) published a review of the current status of iceberg transportation for freshwater supply. In that review the author concluded that conventional towing transportation systems were economically unviable because of the high cost of fuel. This insight set the scene for studies throughout the 1980s, which often focused on alternative means of transportation (Smith, 1978; Connell, 1982[28]; Rowden-Rich, 1982; Sobinger, 1986). These studies highlighted the economic feasibility of iceberg transportation

[27] http://www.igsoc.org/journal/32/111/igs_journal_vol32_issue111_pg242-251.pdf
[28] http://www.freepatentsonline.com/4334873.html

over short distances, revealed cheaper ways of transportation based on non-fossil energy sources, and saw the development of new methods for collecting iceberg melted water.

The research programs developed during this decade, Australian projects, Sobinger's project, Polarstern expedition that I will discuss in this section have been focused on:

- icebergs detection, location and selection;
- icebergs behaviour during transportation (melting rate);
- icebergs wrapping, bagging and maritime current drifting;
- transportation routes, towing and sailing using non fossil energy;
- freshwater delivery at destination.

5.4.1 Australian Projects in the 1980s

The Australian entrepreneur Smith proposed transporting five 40,000 t icebergs from Antarctica to Australia to supply freshwater to Adelaide, South Australia (Smith, 1982[29]). His team proposed using a tugboat and the currents of the Southern Ocean to assist in a transportation process that was scheduled to take five months. Smith's team proposed a system that would moor and protect the delivered icebergs with a skirt (or a dam). Having arrived at their destination, icebergs would be 'mined' with a strong flexible floating boom and small pieces of ice would be transported to a coastal reservoir where a wave generator would increase the rate of melt (Figure 5.14).

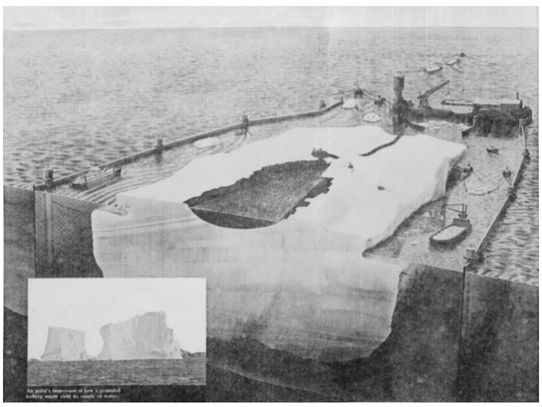


Figure 5.14 Hypothetical Iceberg in a Flexible Floating Boom Skirt, Mined and Transported (credit Keys and Williams, Omega, Sept/Oct 1982 n.p.)

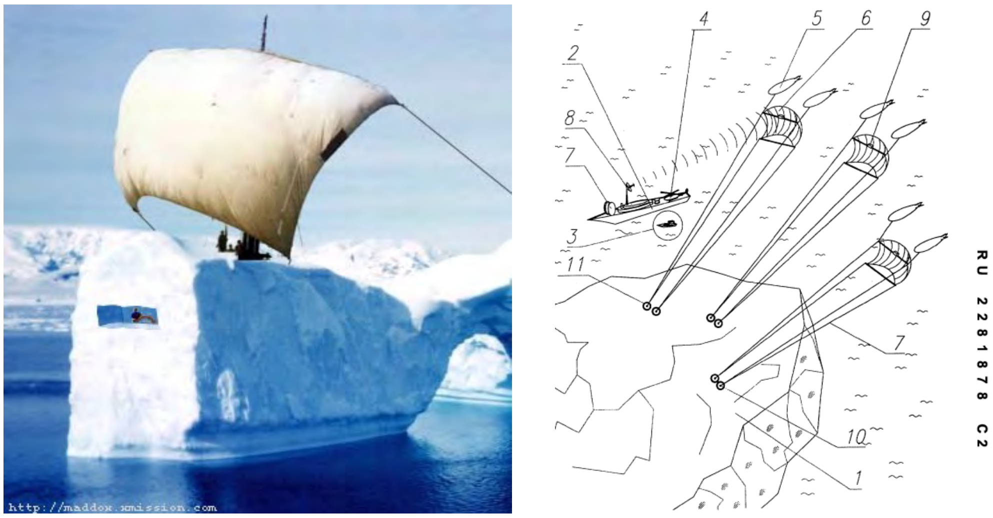
[29] http://www.orf.i.net.au/, http://www.orf.org.au/test/Antarctica2001Report.doc http://www.orf.org.au/test/mawson_centeneryMay2006.htm

The melt water was expected to be collected with 20 m long barges located on the sides of the icebergs at the waterline interface. The plant would utilise the natural thermal gradient between the temperatures of the iceberg water and the sea water to melt the icebergs. However, the mining process was too expensive to conduct and the project was seen as too adventurous. Smith's proposal has been a source of inspiration for later iceberg projects. Key aspects of his project, including the icebergs' proposed routes, the skirt, and the melting rate measurements in situ are still relevant to contemporary iceberg transportation projects.

In 1982 the Australian scientist Rowden-Rich created a company called Ocean Research to study the transportation of icebergs from Antarctica to South Australia (Rowden-Rich, 1982). He reviewed different iceberg transportation techniques, proposed methods to increase the buoyancy of the transported icebergs and proposed to attach sails to the wrapped iceberg in order to use wind energy to reduce fuel transportation costs. Mauviel (1979) previously carried out experiments to model the efficiency of sails propulsion on icebergs (See Appendix 6).

Rowden-Rich (1986) focused on small waterproof wrapped icebergs (500,000 t), and proposed to use the currents for iceberg transportation. Once off the Australian coast, the iceberg melting rate would be increased by cutting and watering. This project was specifically designed for Australia and illustrated how iceberg transportation evolved from oil based systems to natural energies based systems, relying more on the natural routes of icebergs. Rowden-Rich's proposal heralded Australia as a unique destination for iceberg transportation with a unique opportunity in terms of sustainability and profitability. His proposal represented the first transportation system relying mainly on the use of non fossil energies. At this time the AAD noted (Quilty, in Parliament of Australia, 1985 p. 711) that Antarctic ice has an "enormous potential to supply Australia and even such water poor areas as Northern Africa and the Middle East". However notwithstanding having published detailed cost studies Rowden-Rich (1986) project did not attract financial support. The monetary investments were considered too risky by financial authorities for Australia and any other country. Rowden-Rich eventually abandoned his project because of lack of financial support.

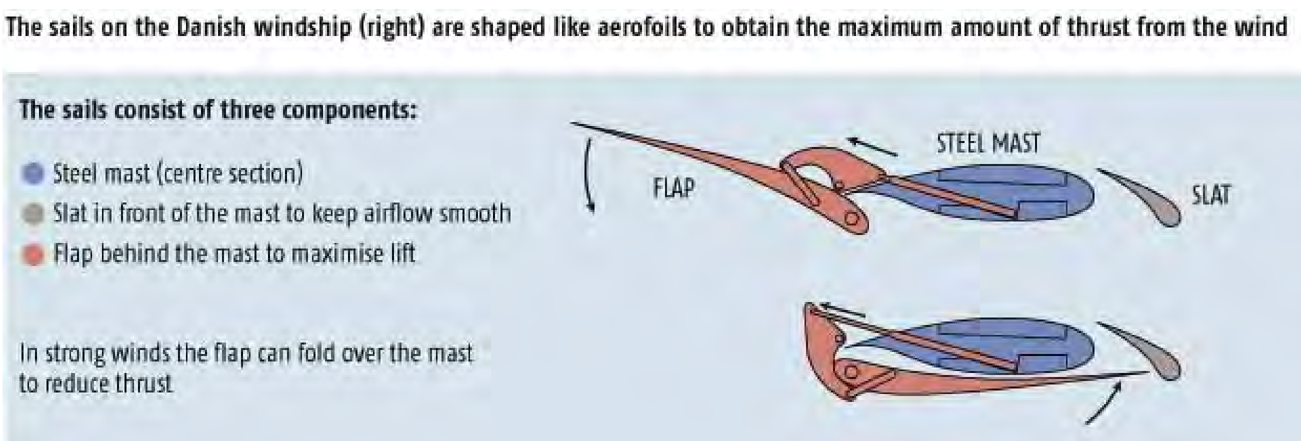
In 2006 Melikov (patent RU 2281878 2006) proposed a similar system having anchors and cables fastened to the icebergs and connected to aerostat sails filled with gas to raise the sail system (Figure 5.15).



a. b.

Figure 5.15 Sailing Iceberg Legend: a. Sail Entertaining Simulation (credit Maddox, 2007[30] n.p.), b. Sailing Iceberg with Multiple Aerostats (credit Melikov, RU 2281878 2006n.p.[31]) Legend: 1 iceberg, 2 tugboat, 5 dirigibles, 6 sail, 8 radio command, 9 connection bare, 10 and 11 anchoring point for sails

The idea to use the wind force and a sail for icebergs propulsion could be further investigated. New types of sails have been designed such as Danish winship sails (Figure 5.16) or more recently Providice[32].



[30]http://www.thebestpageintheuniverse.net/c.cgi?u=af07_more_truth
[31]http://www.ntpo.com/patents_water/water_1/water_684.shtml
[32] http://providice.com/acc-1.html

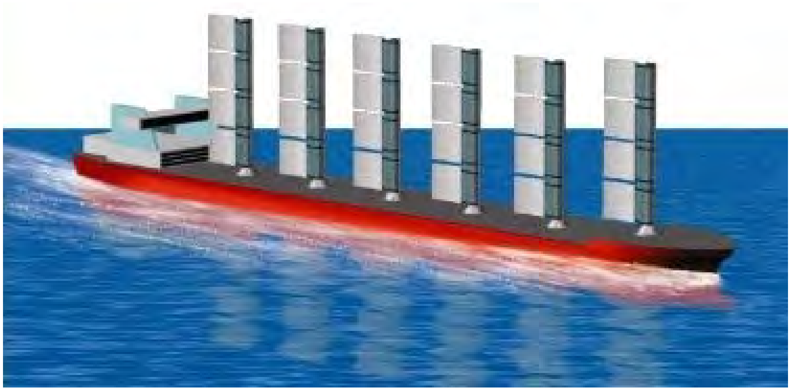


Figure 5.16 New Types of Sails (credit Hamer, 2005[33] p. 44)

5.4.2 Sobinger's Project

In the mid-1980s, Sobinger (1985) worked on developing what would become an original 'Sobinger project' for iceberg freshwater transportation. He calculated the regeneration rates of icebergs and found that tabular icebergs of a size suitable for a commercial operation were released in Antarctica on a continuous and steady yearly basis. Sobinger (1985) noted that the main reason why previous projects have failed was the costs of the experiments. The amount of US$70 million was a critical threshold in expenditure for iceberg transportation. Technical problems related to real scales were not addressed.

The purpose of his research was to tow a small 0.3 km^2 tabular iceberg of 300-350 million t, requiring a towing power of around 450,000 hp, from the Antarctic Peninsula to deliver freshwater anywhere in the world. He proposed an innovative transportation system involving wrapping icebergs in bags (Figure 5.17).

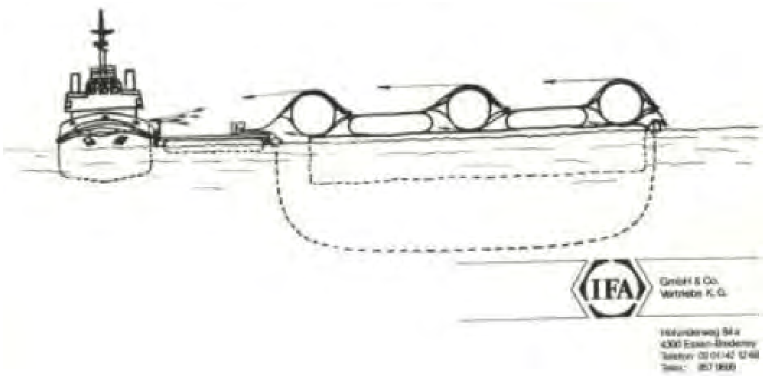


Figure 5.17a Sobinger's Project for Wrapping an Iceberg (credit Sobinger 1985 p. IX)

[33]http://www.newscientist.com/data/images/archive/2488/24881601.jpg

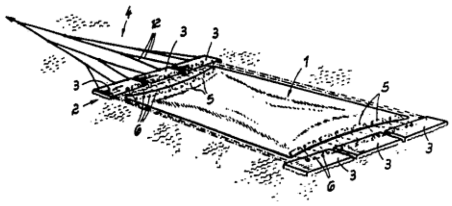


Figure 5.17b Sobinger's Project for Wrapping an Iceberg (credit Sobinger 1985 p. X)
Legend: 1 bag 2 towing bar 3 towing bars 4 cables 5 loops 6 loops 12 cables for towing net

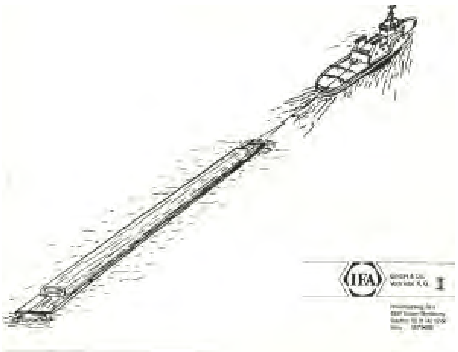


Figure 5.17c Sobinger's Project for Transporting an Iceberg (credit Sobinger 1985 p. II)

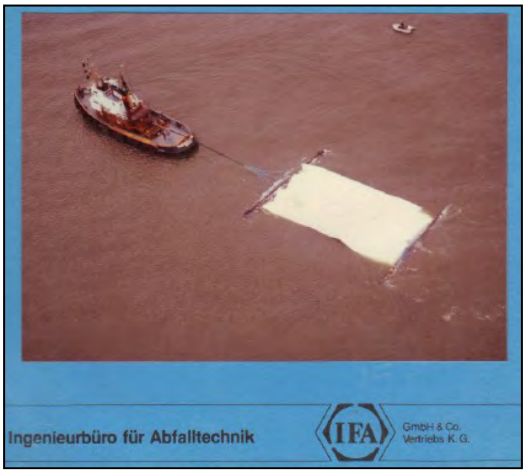


Figure 5.17d Sobinger's Project for Wrapping an Iceberg (credit Sobinger 1985 front page)

The phases of the Sobinger project were:

1. phase one was focused on reviewing the existing literature on iceberg drifting patterns, melting rates, water quality, potential for obtaining freshwater and ecological considerations;

2. phase two was related to the selection of the wrapping foil that would be used to wrap the iceberg. This phase also required simulations in the North Sea that investigated procedures for harnessing and wrapping icebergs, the towing power of various boats, and the study of iceberg melting times*;*
3. phase three examined experiments of the bags/sacks in winds and waves, the air pressure, towing gear, studying the behaviours and acting forces on the tow gear, the lateral reinforcement of bags, the towing force distribution into the bag, the general behaviour of the sack towed at three knots, and the general manoeuvring of icebergs;
4. phase four was devoted to testing at sea a wrapped ice block of 3,000 t.

Sobinger's study demonstrated that it was possible to completely wrap an iceberg at sea in a fibre-reinforced plastic film in calm oceanic conditions. A streamlined waterbag allowed a reduction in the towing power required to transport the iceberg. Sobinger assessed that 800 kW were needed to tow 300,000 t of melted iceberg water in a bag at a speed of three knots, instead of 2,200 kW of fossil fuel for the same volume of water in the form of an iceberg (Sobinger, 1985). The experiments were undertaken at the Hamburg Shipbuilding and Experimental Institute and *in situ* with the German icebreaker *RV Polarstern*. Iceberg wrapping has been experimented on an ice floe of 3,000 t. This experiment can be extended to an iceberg of 1 million t[34]. The test was executed on the 3,000 t iceberg with a tug going into the upstream side of the iceberg using welded 2 m wide enrolled plastic sheet. The main steps were the following:

- the plastic sheet was dropped by gravitation under the iceberg;
- the plastic sheet was aligned to the iceberg by the current;
- the current moved the plastic sheet downstream until the end of the iceberg;
- the underside of the iceberg was provided with airbags to help the plastic sheet to rise, excluding the sea water and lifting the plastic sheet to the top;
- on top of the iceberg, air filled rollers were installed to overcome the friction between the sheet and the ice;
- on the top of the iceberg, the plastic sheet was pulled by cables installed on the tug;
- the plastic sheets had been welded, forming a giant bag;
- the giant bag covering the iceberg could be towed to the currents for transportation to its required destination.

[34] www.freedrinkingwater.com/water_quality/quality1/13-08-icebergs-for-drinking-water.htm

Sobinger (1985 and 1986) pointed out the following advantages of using bags for transporting icebergs and the freshwater produced by icebergs:

- no more melting losses are incurred as the iceberg melts in the bag;
- very small towing power is required due to the optimal flow resistance of bags;
- the ability to transport a larger variety of icebergs; small icebergs (300,000 to 1 million t) are preferred;
- Bags can be reused and the same bag can be used as a storage tank, when the melted water is continuously consumed; no investment are required for additional water storage;
- selecting the bags size according to the destination harbour facilities is simple;
- low expenses for water transportation and storage.

5.4.3 Polarstern Expeditions

Since 1982, the German icebreaker *RV Polarstern* (Figure 5.18) has completed more than 30 expeditions in the Arctic and the Antarctic.

Figure 5.18 *RV Polarstern* in Antarctic (credit Alfred Wegener Institute[35], 2007 n.p.)

The 1984 expedition in Antarctica in collaboration with the German Hydrological Institute was undertaken to observe measure and classify icebergs in the Weddell Sea. It also assessed whether meteorological conditions during summer months in the Antarctic are favourable for icebergs wrapping. According to the Polarstern Expedition Report 1984/1985

[35] blogs.nature.com/climatefeedback/ocean.jpg,www.treehugger.com/R_V-Polarstern-floating-la

(Hempel, 1985) the main achievements of this expedition have been related to the following aspects:

- the icebergs can be selected and wrapped;
- the testing of procedures for wrapping an iceberg of 300,000 t;
- an air-filled roller system was developed to wrap the iceberg;
- experimental technology for welding the wrapping sheet;
- the behaviour of the wrapped iceberg;
- the handling of the air released during the melting of the iceberg;
- the towing force for a relatively thin and flexible foil for wrapping;
- the stability of wrapped iceberg;
- the quality of the melted freshwater was tested, and found as appropriated for human; consumption as drinking water.

Sobinger (1985) designed a specific 'mega bag' for insulating the iceberg from sea water and towing it. During melting the mega bag is in an unstable situation, because of the modification of the centre of gravity of the bag. For transportation the mega bag (in which the iceberg was slid) must be towed. On the mega bag, loops enabling uniform distribution of traction forces during towing were attached. This approach improved the stability of the mega bag during towing and transportation. Further assessment needed to be undertaken.

5.4.4 Other Projects in the 1980s

In the 1970s, exotic methods (feathered paddle wheels, parachutes, osmotic propulsion, kedging or self-propulsion) of transporting icebergs were imagined (Heizer, 1978; Husseiny, 1978; DeMarle, 1979; Weeks, 1980). Later on, Camirand *et al.*, (1981[36]) designed a patent to operate iceberg with an OTEC ocean thermal energy conversion plant (Figure 5.19).

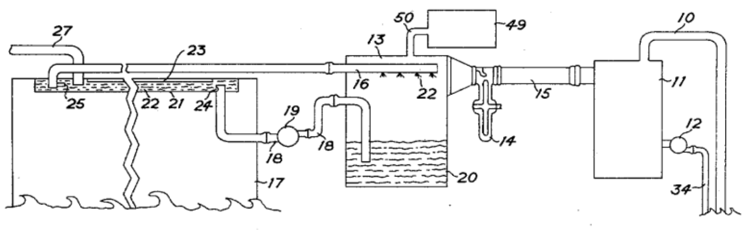


Figure 5.19 Iceberg OTEC Plant (credit Camirand *et al.*, 1981 p .1[37])

[36] http://www.freepatentsonline.com/4295333.pdf
[37] http://www.freepatentsonline.com/4295333.pdf

Both Connell (1982) and Cohen (1982) studied the potential to produce fresh water and energy from icebergs. According to Cohen (1982), the advantages of using icebergs to generate energy relates to their ability to lower the condensing temperature of conventional stations operating with fossil fuels (Figure 5.20).

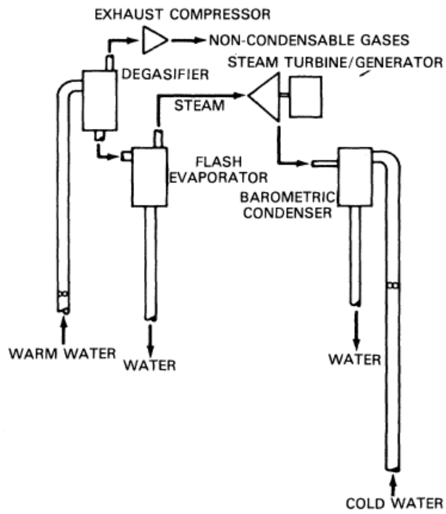


Figure 5.20 The OTEC Ocean Thermal Energy Conversion Open-cycle System or Claude Cycle, used flash evaporation of seawater under a partial vacuum (credit Cohen[38], 1982 p. 412)

Connell (1982[39]) designed a self-propelled tabular iceberg system. This system is based on the conversion of the iceberg melted water gravity to create a propulsive power (Figure 5.21 and Figure 5.22).

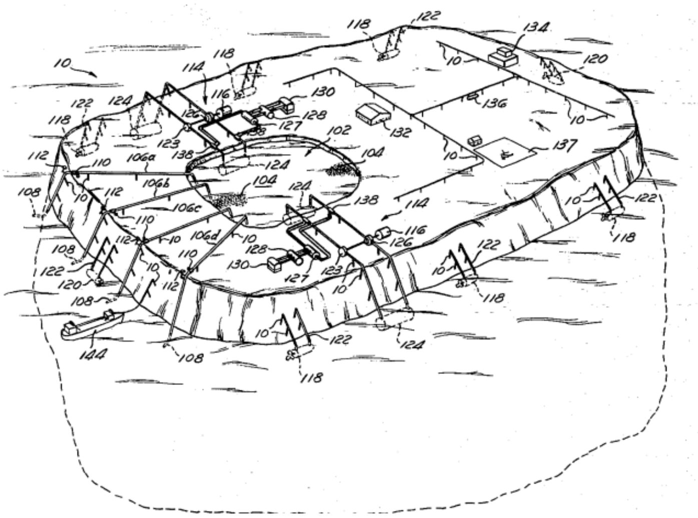


Figure 5.21 Iceberg Wrapping (credit Connell, 1982 p. 1)

[38] http://www.freepatentsonline.com/4334873.html
[39] http://www.freepatentsonline.com/4334873.html

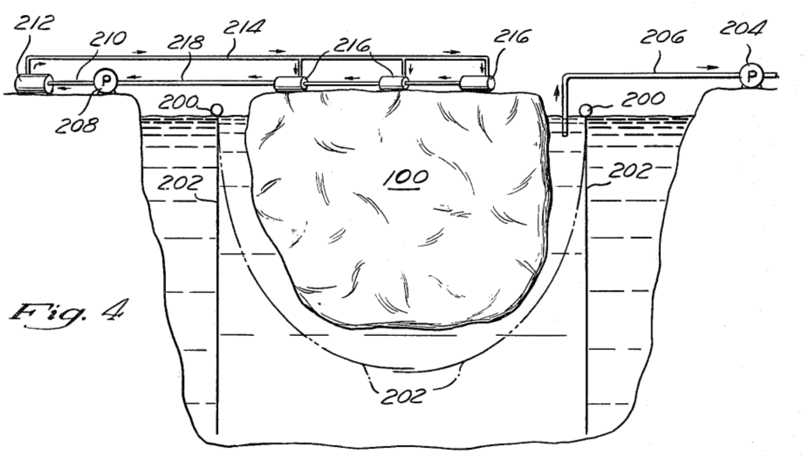


Figure 5.22 Iceberg Operating (credit Connell, 1982[40] p. 3)

According to Connell (1982) (in Husseiny, 1978 p. 359): "the temperature differential between the iceberg and the surrounding water is used to power a heat cycle engine, which, in turn, drives a generator to provide electricity which runs propeller drive motors".

This technology was developed in the 1990s[41], with commercial market applications[42] providing electricity and by-products such as drinking fresh water, as can be seen from Figure 5.23 (Bharathan *et al*., 1990).

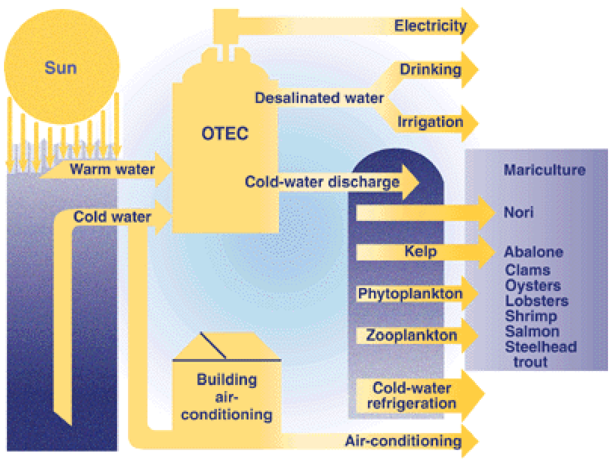


Figure 5.23 OTEC Commercial Applications (credit National Renewable Energy Laboratory US[43], visited October 2010 n.p.)

[40] http://www.freepatentsonline.com/4334873.html
[41] http://www.lockheedmartin.com/products/OTEC/index.html
[42] http://www.nrel.gov/otec/

5.5 Projects and Studies in the 1990s

In the 1990s technologies emerged based on the conversion of the substantial potential resource of the oceans as the renewable energy (tides, currents, waves, salinity and thermal gradients of sea water). The thermal resource of the oceans is assessed as a function of geography, site considerations, constructability, locations, seasonally and daily weather cycles, and environmental impacts. These elements have been considered in the development of technologies for buildings and deploying offshore petroleum facilities that can resist and avoid icebergs mechanical impact.

During the last decade of 20th century, two main projects related to icebergs transportation have been reported, namely the American 'Alaskan Project' and a Canadian project proposed by the C-CORE which developed the most advanced techniques in terms of iceberg harnessing. The C-CORE conducted research for many years on iceberg manoeuvring to protect offshore petrol platforms. This shows how on-going research had positive results in terms of developing practical operational skills that could be used for iceberg transportation. These two projects will be discussed in this section.

5.5.1 Alaskan Iceberg Project

Davidge (1994[44]), from the Alaska Hydrologic Survey Department of Natural Resources, USA was involved in the 1990s in a water transportation project associated with waterbag companies. As 75% of Alaskan water is stored in glacial ice, he considered that waterbags could transport water from several sources such as iceberg ice, rivers, underground water, or Alaskan icebergs. Davidge (1994) assessed the key problems related to the market demand for freshwater, by reviewing several types of bags, comparing their characteristics and calculating the drag forces for a case study of waterbag transportation of Alaskan water to southern US states. He compared the costs and benefits of several water delivery systems (pipelines, tankers, bags and tugboats) and concluded that waterbag transportation was economically more profitable.

[43] http://www.nrel.gov/otec/applications.html
[44] http://www.waterbank.com/Newsletters/nws12.html

5.5.2 Canadian Projects

In Canada, the Centre for Cold Resources Engineering based at the University of Newfoundland in St. John's and the Ocean Research and Development Corporation Limited, a Canadian private company, were both involved in the detection of icebergs in the Northern Hemisphere in the early years of iceberg transportation research (LeDrew and Culshaw, 1977).

In 1982 in Canada, the C-CORE designed a more ambitious iceberg transportation project (ICE Eng. - R42 - Icebergs Field Survey See also ICE Eng. for MacLaren Plansearch[45]) consisting of selecting icebergs, towing and then cutting them into small sections and transporting them by trucks from Newfoundland to North America (Bosma, 1979). The technology developed in Canada for harnessing and towing has been an invaluable step for future iceberg transportation projects. It was concluded that Newfoundland was an ideal region for iceberg towing because of the potential benefits for commercial maritime routes, fishing zones and for the offshore petroleum and gas industry. The 1990s research activity in Canada has enhanced the development of high technological standards for iceberg detection, towing and harvesting. The growing range of satellites and radar technologies minimised the possible gaps in spatial temporal, meteorological and environmental conditions. However, the problems of cutting up or destroying icebergs appeared to be too expensive to study icebergs harvesting on a larger scale (Diemand, 2001).The Canadian research activity for icebergs harvesting during the 1990s inspired the processes in use today in the Grand Banks of Newfoundland on the East Coast of Canada. The technologies for detection and towing of icebergs are in common management practice by the International Ice Patrol. The icebergs harvesting technologies have a huge economic and financial impact on the safety of offshore petroleum and gas facilities, avoiding collision and protecting maritime navigation in the North Atlantic.

First attempts of commercial utilisation of iceberg for bottled freshwater started in Canada in 1986. In 1995 vodka production from iceberg water started in Newfoundland, based on the harvesting of small quantities of iceberg ice.

Having in mind that icebergs are a perennial source of freshwater, I will investigate later in my thesis, to which extent the technologies developed in the Northern Hemisphere can be

[45] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Berg_shapes_99.pdf

adapted, for iceberg transportation in the Southern Hemisphere, from Antarctica to Australia or other destinations over the world.

5.6 Recent Projects in Early Years of the 21st century

According to PERD/CHC Report 20-84 (2007[46]), the production of icebergs has recently increased at an unprecedented rate in response to rapid air and ocean temperature warming in the last decade. However in the first decade of the 21st century studies on iceberg transportation were still marginal (Smakhtin *et al*., 2001[47]). Two studies were undertaken by the Iceberg Water Harvesting Group (IWHG), formed in Munich in 1998, and by the South African Division of Water. Smakthin *et al*. (2001), from the South African Division of Water, proposed to tow icebergs from Antarctica to South Africa in order to develop freshwater resources for African countries where there is an enormous deficit in freshwater. In this project, icebergs would be steered rather than towed using the kinematics of iceberg drift by maritime currents. The IWHG have proposed a new technology converting naturally occurring ocean phenomena, such as currents, waves, salinity gradients and melting kinetics, that optimised the routing for individual icebergs. Icebergs routes can be simulated using advance computing models. The modelling included the following aims: minimisation of energy input for tugs, minimisation of travelling time, and maximisation of the ice mass at the destination site. In this proposal, the icebergs would complete a substantial part of the navigation by tracing their natural path and by drifting on currents with winds. However the principles of this project can be described: the study argued that sublimation melting rates needed to be calculated depending on the sizes, routes and travel durations of icebergs. Smakthin *et al*. (2001) noted also that the stability of the iceberg during transportation is a major concern for the success of icebergs management (Smakthin *et al*., 2001).

The 2000s were a productive time for iceberg transportation technical designs. Fuerle (2003[48]) worked on a project of iceberg transportation and designed models of bags. Shick (2004[49]) and Abramovitch (2004[50]) also presented patents with detailed technical elements. These projects are however focusing on very specific aspects of transportation such as bags, propulsions and stability issues. These designs are technical and also represent a valuable conceptual contribution for iceberg transportation. Abramovitch (2004) studied the use of on

[46] ftp://ftp2.chc.nrc.ca/CRTreports/GB_Iceberg_Manage_Overview_07.pdf
[47] http://www.waternet.co.za/we/docs/pete_unconventional_sources.pdf
[48] http://www.freepatentsonline.com/6616376.html
[49] http://www.freepatentsonline.com/6688105.html
[50] http://www.freepatentsonline.com/y2004/0265062.html

enrolled double layers cloths tightened by belts around the iceberg for melted freshwater collection. Kazlousky (2010) studied also a double layered clothing.

Iceberg transportation was considered later in 2004 by a group of British entrepreneurs to transport icebergs from the coasts of Canada to Portugal which was facing a crisis of water shortage. Two years later, in 2006, the British company Thames Water considered to tow an iceberg from the Arctic to England to provide an emergency water supply in response to a shortage crisis. The largest sized projects for iceberg transportation was conceptualised by Thames Water Comp. UK which intended to tow Arctic icebergs up Thames River in a train of barges (Smith, 2006). However, like many iceberg transportation proposals, interest waned and the project was abandoned soon after. Wadhams and his group from the University of Cambridge, Orheim and Mougin are working on a project of thermal plants modelling using icebergs (Wadhams, 2009).

5.7 Patents for Iceberg Transportation, Bagging and Propulsion

In this section I will summarise the patents relating to production of freshwater from icebergs and icebergs transportation, bagging and propulsion which have been published since the First International Conference on Icebergs Transportation held in 1977. The patents are described in Table 5.2.

Table 5.2 Patents on Melted Freshwater and Icebergs Transportation

Patent number and author	**Patent title**
US Patent 3289415 12/1966 Author: Merrill	Method and Apparatus for Transporting Potable Water
US Patent 4258640 03/1981 Author: Mougin	Tabular iceberg protecting device
US Patent 4289423 09/1981 Author: Mougin	Protective skirt for an iceberg
US Patent 4299184, 11/1981 Author: Mougin	Method of towing large masses
US patent 4334873 06/1982 Author: Connell	Iceberg propulsion system
European Patent WO005609 12/1985 DE 3327242 DE 1983333 15744 19830430 Author: Sobinger	Flexible cohering for icebergs, flexible casing for icebergs, Regular distribution of a traction force.
US Patent no 4854780, 1989 Author: Hewlings	Damping waves towing. System with ice field
US Patent no 6616376, 2003 Author: Fuerle	Bagging icebergs
US patent no 6688105, 2004 Author: Shick	Icebergs utilisation process
US patent no 0265062, 2004 Author: Abramovitch	Icebergs insulation method for freshwater production
RU 2281878 2006 Author: Melikov	Sailing Iceberg with Multiple Aerostats filled with gas
European Patent WO/099797 09/2010 Author: Kazlousky	Shell for Packing and Method for Iceberg Transporting

The patents submitted by Mougin (1980[51]) for icebergs transportation introduced protective flexible panels for thermal and mechanical protection of icebergs against wave erosion (Figure 5.24).

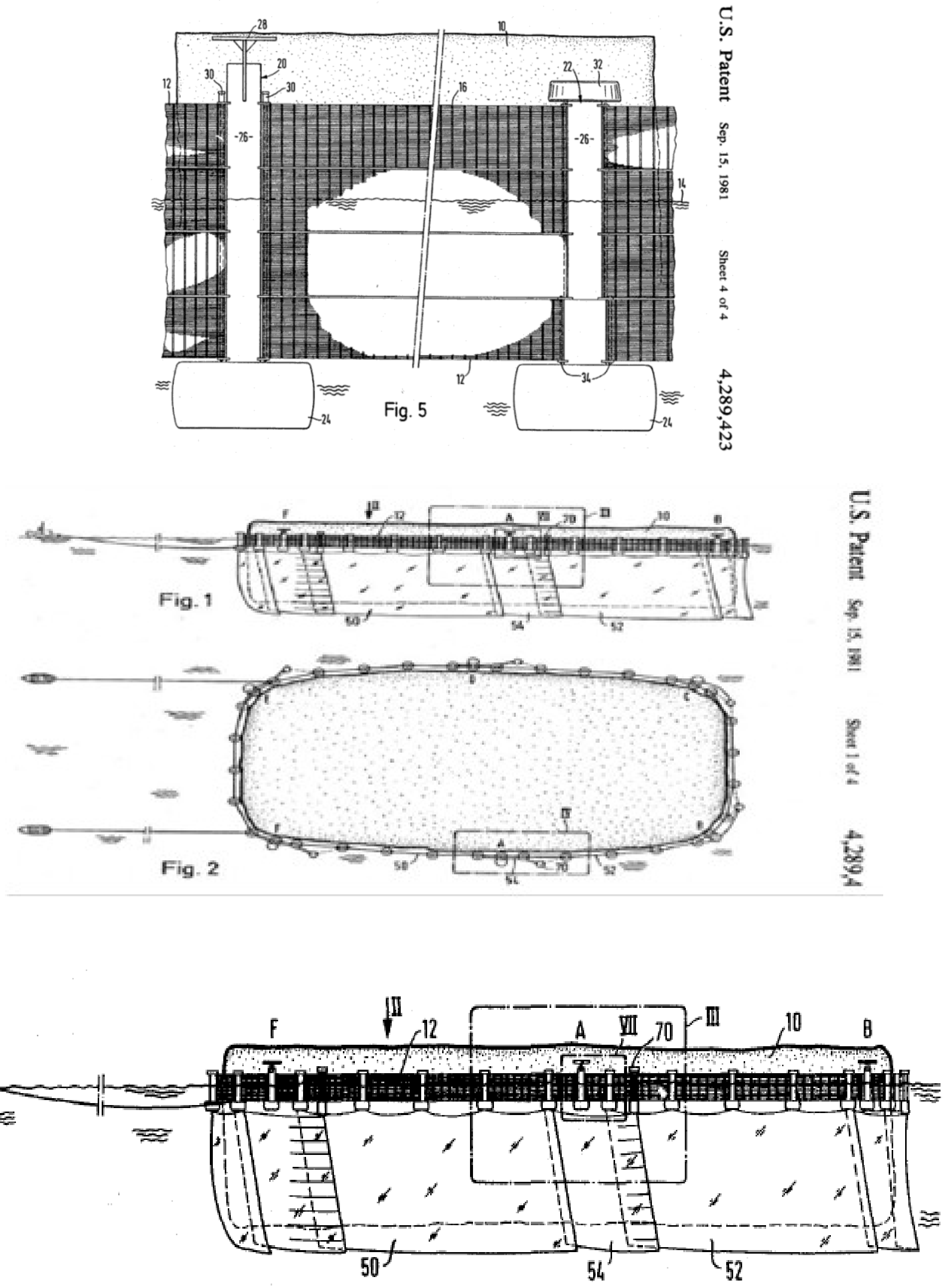


Figure 5.24 Model of Iceberg Skirt (credit Mougin, US Patent 4,289,423 Figure 1 and 2 1981 n.p.) Legend: A to F particular winch post; 10: tabular iceberg; 12: panels of protective skirt; 18: horizontal straps; 20: winch post; 21,22,23: intermediate post; 24: buoyancy chamber of floating post; 40,42: tugs; 50,52, 54:main spans of lower protective portion;

[51] http://www.freepatentsonline.com/4223627.html, http://www.freepatentsonline.com/4178872.html, http://www.freepatentsonline.com/4177748.html, http://www.docstoc.com/docs/43650817/Method-Of-Manufacturing-A-Protective-Skirt-For-A-Tabular-Iceberg---Patent-4172751

Connell (1982) designed a patent in which he proposed an innovative propulsion mechanism for long distance icebergs transportation requiring minimum fossil energy. Two sub-mechanisms were discussed, the first related to the gravity flow of melted ice and the second using temperature differentials between the iceberg and the surrounding sea water. The mechanisms were meant to produce a propulsion power up to 2,000 HP. Sobinger's patent concerned a insulating iceberg megabag (Sobinger, 1986). Hewlings (1989[52]) designed a patent which did not concern a large scale iceberg transportation system directly but he developed and designed a shield collar that could be used to protect the delimited field of ice from collision with other icebergs and from wave erosion. The edge of the bag opening is equipped by a float connected to a buoy. The large bag could be used to transport the melt water and the iceberg (Figure 5.25).

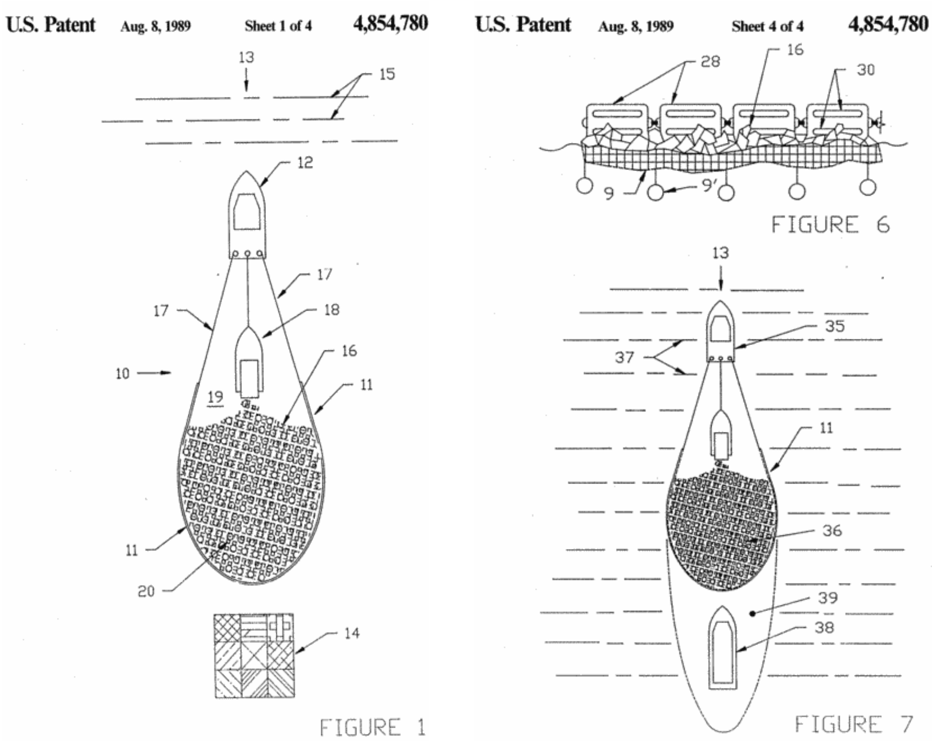


Figure 5.25 System of Damping Waves (credit Hewlings US Patent 4,854,780 1989 Figure 1, Figure 6, Figure 7 n.p.)

Fuerle (2003) proposed a detailed logistic process for bagging an iceberg slid in a large bag (Figure 5.26, Figure 5.27 and figure 5.28).

[52] http://www.freepatentsonline.com/4854780.html

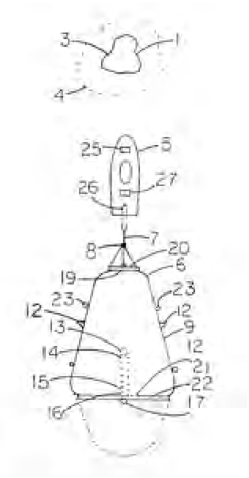


Figure 5.26 System of Iceberg Bagging (credit US Patent no 6,616,376, 2003 p. 1)

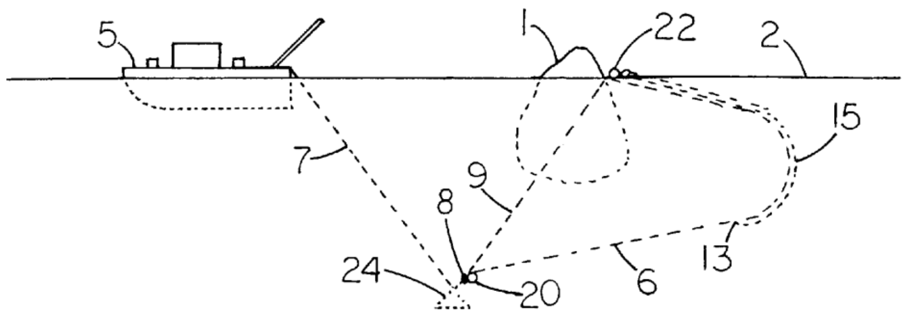


FIG. 4

Figure 5.27 System of Iceberg Bagging (credit US Patent no 6,616,376, 2003 p. 5)

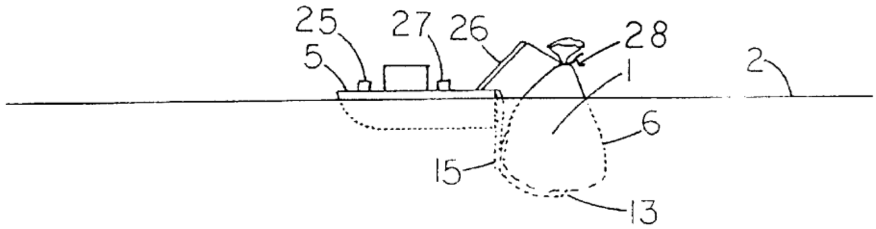


FIG. 6

Figure 5.28 System of Iceberg Bagging (credit US Patent no 6,616,376, 2003 p. 7)

Shick (2004) studied icebergs transportation from Antarctica to a coastal destination. During transportation the iceberg is protected against thermal decay by a kelp netting system

(Figure 5.29). At the destination, the iceberg is towed with a submersible tug into a carved channel. The iceberg is enclosed in the container, slowly delivering freshwater.

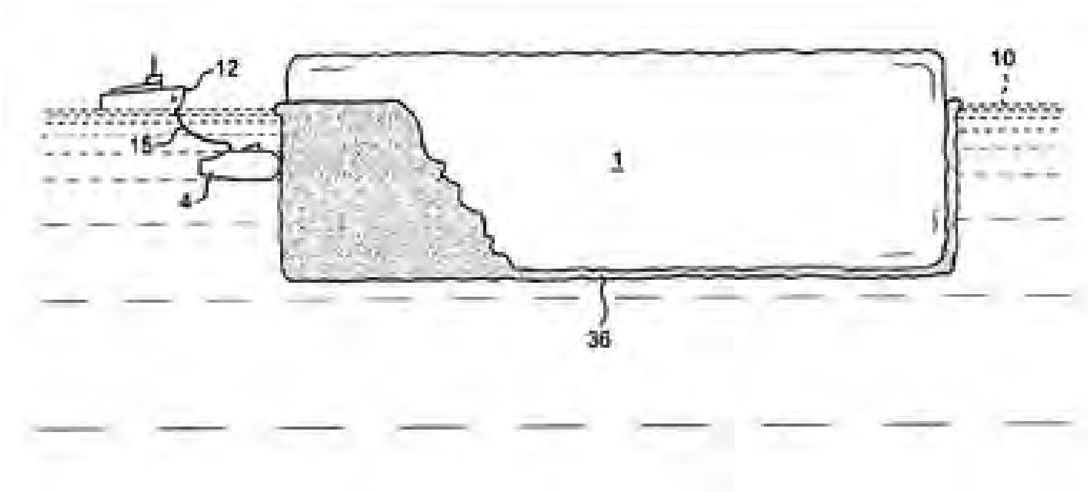


Figure 5.29 Kelp netting System (credit Shick, 2004 p. 9[53])

Abramovitch (2004) designed a protective iceberg cloth as shown in Figure 5.30.

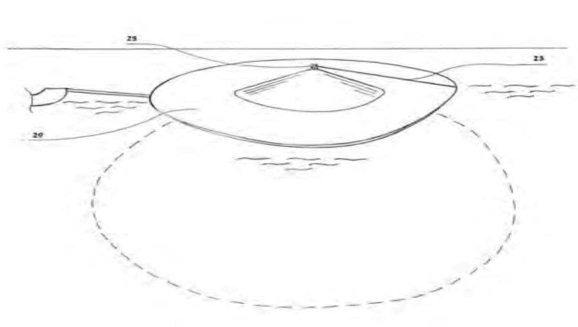


Figure 5.30 Protective Cloth of the Iceberg (credit Abramovitch, US Patent 20,040,265,062, Figure 1 2004 n.p.)

The cloth is a double layered water proof foil, tightened by belts in separate cells. The cloth cells are connected to a net of pipes acting as connection lines (Figure 5.31). Some of the connection lines conduct the air to inflate the cells and other connection lines collect the melted water at the destination. The cloth insulating bag is used for both transportation of melted water and its delivery at destination.

[53] http://www.wikipatents.com/US-Patent-6688105/iceberg-utilization-process-improvement

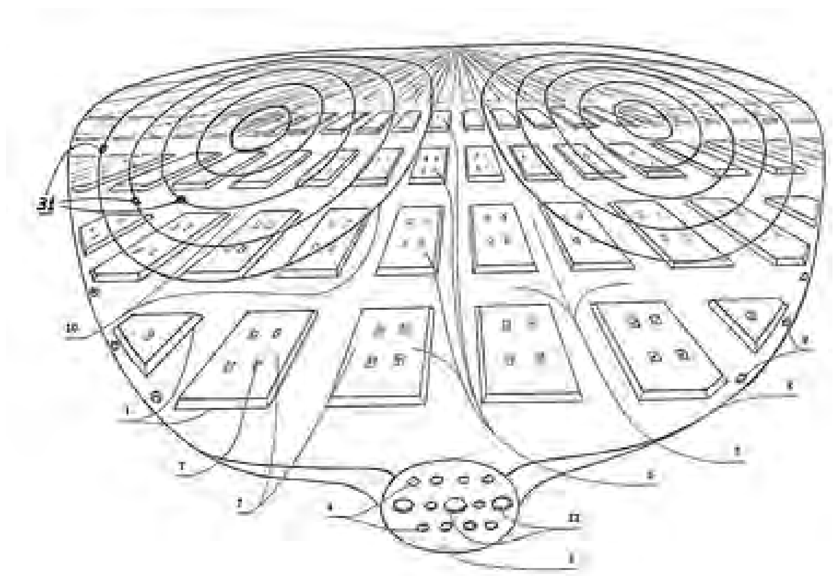


Figure 5.31 Cells in the Cloth Wall (credit Abramovitch, US Patent 20,040,265,062 2004 n.p.)
Legend: Connection lines 1 cover all the cloth in the shape of a net with separate cells in the form of squares or rectangles representing air cushions 2

In 2010, Kazlousky patented a case of transporting iceberg (Figure 5.32).

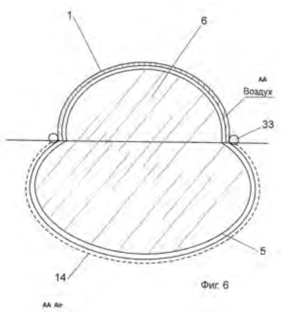


Figure 5.32 Shell for Packing an Iceberg and a Method for Transporting said Iceberg (credit Kazlousky, 10.09.2010 WO/2010/099797 p. 1[54])

This patent proposes a mirror-like reflective coating for the iceberg case to enhance the melting.

My critical analysis of these patents is related to the following points:

[54]http://www.wipo.int/pctdb/images/PCT-IMAGES/10092010/EA2010000002_10092010_gz_en.x4-b.jpg, http://www.wipo.int/pctdb/en/wo.jsp?WO=2010099797&IA=EA2010000002&DISPLAY=STATUS

- the iceberg floating in a progressively increasing quantity of melted water in the bag creates a problem of stability, modifies the iceberg's centre of gravity and produces shocks between the solid ice and the walls of the bag, increasing risks of bag breakage. The patents studied did not assess enough the stability problem associated with wrapped melted iceberg during drifting and transportation;
- the use of bags for icebergs transportation has not progressed to a practical stage;
- the patents were not subject to intensive technical development;
- new materials derived from space industry research have not been used to date for bags;
- the technological studies are not reliable as they do not measure, the risks and the costs associated with the development of untested icebergs transportation technologies.

5.8 Discussion

Previous projects have failed to live up to expectations for different reasons which will be discussed below. Having in mind the physical characteristics of icebergs and the harnessing related hazards, to develop an efficient transportation system (suitable resource and destination locations, large capacity, sustainable technical operating process, low cost) the questions which need to be answered are:

- What are the needs and the required capacity for iceberg melt freshwater?

WA could use between 2 and 20 km^3 on different time scale. A maximum of 200 km^3 would be appropriate in environmental terms. Transporting iceberg water from the SAF to WA would using wind and current energies, the circumpolar geography of Antarctica could, evidently, provide access from the AAT to WA regions interested in fresh water from iceberg resources.

- Where are suitable sources and destination locations?

Locations of major shipping routes are of strategic interest (Rodrigue and Notteboom, 2009[55]). For a large iceberg transportation system, West Australia could be an optimal location in terms of relative proximity to the iceberg resource location in Antarctica, provision of existing infrastructure, the ability to take advantage of water currents, as well as having a high demand for large volumes of freshwater.

[55] http://people.hofstra.edu/Jean-paul_Rodrigue/downloads/Rodrigue+Notteboom-paper-JTG-draft.pdf

Thanks to the advances with previous projects and remote sensing technologies it is possible to accurately locate Antarctic icebergs resources. The major routes of iceberg movements have been tracked and mapped using satellite technology and are consequently well known and predictable. For example, the British Antarctic Survey have provided detailed surveys of icebergs production drift and decay. The International Ice Patrol locates icebergs on a daily basis in order to alert shipping traffic. The Sea International Authorities (SIA) and the International Maritime Organisation (IMO) also deliver daily complementary data on iceberg activity.

As a specialised industrial activity, transporting icebergs to supply freshwater is affected by local and regional characteristics. It requires a supply destination optimally located in terms of demand, distance, environmental characteristics, and infrastructure. In most iceberg transportation projects, the transportation system (comprising the iceberg and the tug) follows a route from Antarctica to various destinations, such as: Saudi Arabia (Montfort and Oudendijk, 1979; Victor, 1979; Connell, 1982), the USA (Hult and Ostrander, 1978; Shick, 2004), or Australia (Weeks and Campbell, 1973, Smith, 1979; Rowden-Rich, 1986). These studies concluded that the technological solutions proposed have not been economically viable. The routes from Antarctica to Saudi Arabia or to the USA were too long and the technology proposed was not able to avoid iceberg decay and melting and to ensure freshwater collection. The propulsion costs using fossil fuel were extremely high. During those days the iceberg transportation systems have been at an early ‘conceptualisation’ stage of development. Routes from Antarctica to Australia are more economically realistic.

> - Considering that iceberg melting would produce modification of iceberg gravity centre, cracking or breaking inducing high hazards for the transportation convoy, what would be the technical solutions to ensure safe iceberg transportation and what could improve stability during transportation?

In the projects described previously, a popular means by which iceberg stability was improved, during transporting process, was by using bags (Merrill, 1966; Hult and Ostrander, 1978; Connell, 1982; Wilson, Frisch and Kresta, 1979; Humphry, 1979; and Hussain, 1979). While these studies advanced arguments for the importance of using bags, they remained either too vague or too specific about the technical deployment of bag technology. Mougin (1980) and Sobinger (1986) proposed more detailed technical designs. Mougin (1980) proposed large bag designs which were not tested and of which the risk of breakage still remained a problem especially considering large scales. Sobinger (1985) proposed a sail cloth bag to wrap an iceberg of 300,000 t, which had been tested in the North Sea. In these experiments the bag was anchored or tied off across the top of the iceberg. However, Sobinger's experiments did not show enough reliability for transportation for Southern Ocean sailing conditions and the scale of iceberg water demand requires bigger and more reliable bagging techniques. Controlling such bags in Southern Ocean conditions is difficult and requires specific meteorological conditions. The design of the Sobinger's bag is suitable to melt the iceberg but not to collect and transport iceberg melt water efficiently which remains an issue.

Another possibility to optimise the iceberg stability consisted in separating the melting water from the decayed iceberg using a collecting bag (Sobinger, 1986; Rowden-Rich, 1984) or enveloping the iceberg in a net (Sobinger, 1986; Hewlings, 1989; Fuerle, 2003; Shick, 2004, C-CORE, 2005a; 2005b; and 2005c; see also Figure 5.33).

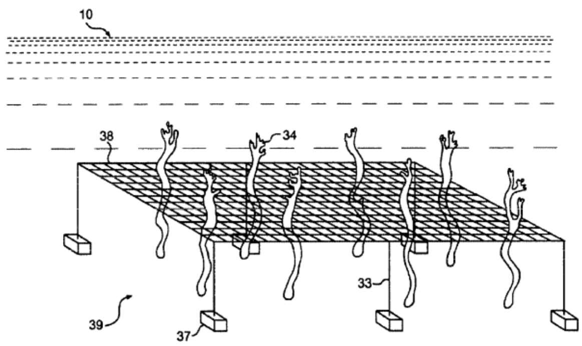


FIG. 2A

Figure 5.33 Kelp Netting (credit Shick 2004 p. 4)

Except Hult and Ostrander, Weeks and Campbell, Mougin and Sobinger's studies which represent the most advanced studies on iceberg transportation systems, the other studies were more 'conceptual' or focusing on one particular aspect of an iceberg transportation system without providing a comprehensive solution for iceberg transportation systems. They were not 'adapted to' any global transportation system.

Technical aspects of the iceberg transportation process, such as train systems to optimise convoy stability, were studied by Hult and Ostrander and Rowden-Rich, could be optimised by improving iceberg stability (decay and collecting of melted water), harnessing, towing transporting and drifting. My thesis aims to assess the potential techniques concerning these aspects.

- Could non fossil fuel (wind, maritime currents) based transportation systems be appropriate for iceberg transportation?

Transportation models are proposed in the literature to optimise transportation propulsion forces, techniques and costs (Serletis, 2007). The optimisation of the distance is mostly derived from the cost of the transportation process. For example: how much distance can be travelled within a given amount of time is not as important as asking how much can the cost of transportation be minimised. The physical or temporal distance matters less than the pure cost of the transportation process, which may be a significant challenge in itself. Over a set distance, this can be achieved by minimising the costs of the energy required. Iceberg transportation systems were traditionally based on towing processes which involved giant tug boats powered by nuclear energy yet used as icebreakers in Polar Regions (Weeks and Campbell, 1979; Hult and Ostrander, 1979; Shick, 2004) or petrol engines (Weeks and Campbell, 1979; Hult and Ostrander,1978 and 1979;Montfort and Oudendijk, 1979; Victor, 1979, Connell, 1982; Smith, 1978 and 1979; Rowden-Rich, 1982 and 1986; Sobinger 1986; Fuerle, 2003; Shick, 2004; Abramovitch, 2004).

Previous studies of iceberg transportation have advocated the use of tug boats to meet the time and distance objectives of bulk maritime transportation, to meet the technological requirements of polar maritime transportation. However, the major obstacle in using tug boats to tow icebergs is the overall cost of operation over a long distance. Iceberg transportation systems that use fossil fuels have high energy costs because of the distances (> 1,000 km) across which icebergs have to be moved. Therefore, an efficient transportation system should optimise the distance covered by the transportation process. The cost of transportation depends mainly on the energy cost, the amount of energy spent during the transportation operation and the infrastructures costs. In the case of iceberg transportation, cheaper energies (winds and maritime currents), or less energy spent, would improve the overall cost and therefore provide easier access to the iceberg resource through a new transportation system. As noted by Serletis (2007) the transportation speed plays a less significant role and efficiency and capacity are more important. The propulsion characteristics of the transportation system need to be adapted to the specificities of the iceberg resource. In previous projects, alternate propulsion systems have been largely limited to conceptual speculation, for example the suggestions made by Connell (1982), Smith (1983) and Rowden-Rich (1984) that giant sails could be used to reduce energy costs. The use of currents to support towing systems has been considered in some cases (Montfort, 1980; Oudendijk, 1978; Smith, 1982; Rowden Rich, 1984; Sobinger, 1986; Smakthin *et al*., 2001). Current or sail based sailing systems seems to me to be the most promising being environmentally friendly. Projects enumerated before, based on non fossil fuel transportation systems, failed because of lack of appropriate technology. However, studying the principles described previously, and having in mind the progress achieved in producing new materials used for air and space applications, it may be possible to find a semi-automatic propulsion system that is cost efficient for iceberg transport systems. New technologies based on wind and maritime currents could be developed. Such a system (which will be described in Chapter 7) would be able of carrying very large icebergs over long distances while remaining stable in extreme climatic conditions. Winds and currents would be favourable.

5.9 Conclusion

This chapter has assessed the range of transportation technologies that have been proposed to transport icebergs. Iceberg transportation projects faced several challenges. This chapter has reviewed the scientific and technical literature published in the last four decades on iceberg transportation. The results from the range of projects commented in this chapter demonstrates the considerable potential that exists for transportation of icebergs and their freshwater. However none of the iceberg transportation projects that have been advanced in the last decade have had an appropriate technical and spatial frame to successfully design a sustainable operating system for icebergs transportation from Antarctica to Australia. Iceberg transportation was considered to be economically unviable. Costs studies did not identify enough potential benefits to progress to a world-scale project. A number of technical issues remained unresolved:

- because of the instability of the convoy, the depth of the iceberg, the melting rates, as well as the energy costs, projects based only on towing technology are judged to be infeasible;
- the freshwater melting losses during transportation issues; In the 1980s new technological advancements were suggested, chief among which was wrapping icebergs in a large bag. Wrapping icebergs techniques have been developed and patented. The pioneering Sobinger's (1985) work was carried out on a full-scale 3,000 t iceberg wrapped in a bag. This experience was carried out on a real scale. Techniques using bags need to be

perfected. No techniques have been designed to ensure a stable iceberg transportation using a bag. In the 1980s the ability to successfully carry out an iceberg transportation project on a large scale was still uncertain. The bags designed were not tested for melting instable iceberg and during transportation in the harsh conditions of the Southern Ocean. To ensure safe iceberg transportation and avoid breaking the bag, techniques inspired by Mougin (1981), Sobinger (1985) and Fuerle (2001) could be adapted to an AAT WA project. Bag technology has changed since the period of these studies and bag costs are certainly lower than in the last century and accessible today;

- iceberg stability issues; the mass metacentre of the iceberg can change because of melting and cause capsizing (Bowring *et al.*, 2010). The iceberg could be stabilised with specific techniques and its behaviour could be controlled while its melt waters could be transported in specific bags which would have the required resistance under the harsh conditions of the Southern Ocean; harnessing icebergs is a crucial aspect of iceberg transportation (C-CORE, 2001a; 2001b; 2002; 2003a; 2004a; 2005a; 2005b; 2005c).
- energy costs; Australian projects submitted by Smith (1983) and by Rowden-Rich (1986, 2004) identified that the currents from Antarctica to Australia were favourable for icebergs drifting, but these maritime currents, like other natural energy sources, are highly variable in force and direction. They assumed the fact that to deliver freshwater melted from icebergs, surface maritime currents could be used to propel icebergs drifting naturally from Antarctica to Australia. However the lack of knowledge on the direction and steadiness of maritime currents from Antarctica to Australia represented the main obstacles for the success of this approach and no techniques had been specifically designed to provide a system for iceberg transportation based mainly on currents, or to provide a steady and consistent direction to icebergs while being transported only by currents.

Putting together all the findings of the previous projects and experiments and analysing them can help to create a new transportation system for freshwater melted from icebergs, from Antarctica to Australia. The use of effective detection harnessing techniques of the C-CORE at larger scales, existing relatively small bags (15,000 t) for collecting melted water and the technical progress of propulsion systems (i.e. wind or current propulsion) could overcome the obstacles of the harvesting of the icebergs resource with substantial investments. In this way it is possible to select areas of research to advance the design of an efficient, sustainable and profitable iceberg transportation system. After examining iceberg transportation projects, the thesis now turns to the technical feasibility and environmental sustainability requirements for my proposed future project which will be outlined in Chapter 7.

Chapter 6 New Technologies for Iceberg Transportation

Figure 6.0a Waterbag Moored at Loading Terminal (credit Monohakobi Institute[1], 2008 n.p.)

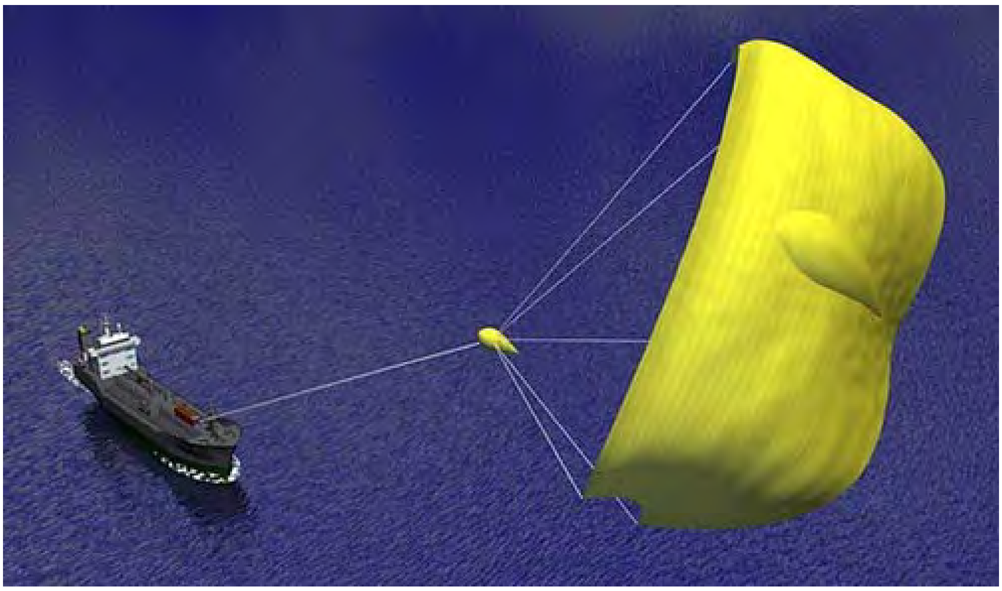


Figure 6.0b Giant Kite for Commercial Cargo Scale Propulsion Prototype (credit Skysails[2], 2006 n.p.)

1 http://www.monohakobi.com/en/research/water_bag/index.html

Chapter 6 New Technologies for Iceberg Transportation

Social and economic evolutions of the 20th century had a major influence on transportation technical progresses. In transportation geography, technological engineering analyses of transportation systems are broken down into a number of components such as: the investigation of the resources available, utilising spatial interaction models to study the motive forces of transport supply on models, the transportation planning, the construction of transportation systems infrastructures and their maintenance. The main outcome of such studies is, in the context of this thesis, to determine what techniques and operating conditions will be suitable for developing an iceberg water transportation system from Antarctica to Australia. Since the 18th century, new technologies have revolutionised polar transportation which became faster and more efficient. In recent years, new transportation techniques have been developed for maritime transportation and were used in projects that could suit the scale and requirements of iceberg transportation. This chapter aims to assess those transportation technologies that would be best suited to the transportation of icebergs and melted freshwater from the AAT to WA.

The objective of this assessment is to identify which techniques could be appropriate to the scale of iceberg transportation and adapted to such transportation in a sustainable manner. It will then be possible to select the combination of components and processes of efficient and sustainable systems of transportation that would be the most valid for the transportation of icebergs and melted freshwater resulting from icebergs. Key criteria for assessing the performance of possible transportation systems include the volume of ice to be transported, the detection of the icebergs and the stability of the systems of transportation. In turn, these considerations raise further questions including:

- what type of detection techniques are available? With which associated accuracy level?
- what type of transporting materials and processes adapted for iceberg might be used?
- what environmental conditions are the most conducive to stable transportation of large volumes (such as icebergs)?
- what type of propulsion is most suited for large volumes?
- what speed could these systems move such volumes (comparable to icebergs)?

[2] http://solaripedia.blogspot.com/2009/10/tethered-sails-power-cargo-ships-with.html

Chapter 5 highlighted the fact that previous iceberg transportation projects based on the management of large ice mass at the operating and destination sites, short travelling time and fossil energy input for icebergs transportation with tugs, have not been successful. We also saw previously how far technical studies went and that a large range of technological options was proposed but were too specific and did not provide a global solution for iceberg transportation systems. Especially, areas such as iceberg selection, the management of iceberg (harvesting and stability) and maritime transportation were not investigated with a specific iceberg sustainable transportation focus.

However, recent technical improvements in these areas of research could ‘fill’ the technological ‘gaps’ of previous projects. This chapter will therefore investigate three aspects of recent innovations: icebergs selection process; icebergs management; new technologies for icebergs transportation and development of water bag technology for melted fresh water; currents and kites to aid the drifting of icebergs.

6.1 Iceberg Detection Techniques

Different techniques are available for iceberg detection. Since tabular icebergs are massive, it is possible to detect them by sight. Orheim (1983) proposed an international logging scheme for iceberg sightings in which considerable details about icebergs can be seen (shape, size, colour, volume, homogeneity). Norwegian Polar Institute (2003) monitored icebergs sightings. However, the visual detection above the sea level of icebergs is severely limited by fog (Figure 6.1).

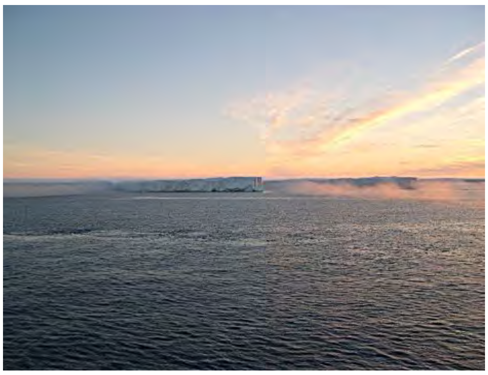


Figure 6.1 Large Tabular Icebergs in Fog in Antarctica (credit Scambos, NSIDC[3] n.d. n.p.)

[3] www.nasa.gov/.../169455main_TedScambos_NSIDC.jpg, see also http://msuinantarctica.blogspot.com/2010_01_01_archive.html

It is also possible to detect icebergs by the sounds caused by high-pressure air bubbles discharge of melting ice in warmer waters (Scambos *et al.*, 2003; 2005). According to Rafferty (2010 p. 168):

> [I]n the open sea, an iceberg produces noise, squealing, popping, and creaking sounds caused by mechanical stresses [induced by melting or colliding] ... In summer, icebergs can also produce a high-pitched hissing sound called bergy seltzer.

These sounds and noises can be detected underwater up to 2 km away (Urich *et al.*, 1971; Scambos *et al.*, 2003; 2005; MacAyeal *et al.*, 2008). Decaying icebergs have to be detected continuously because they are often surrounded by growlers and bergy bits which represent potential threats to maritime transportation.

However nowadays there is a heavy reliance on remote sensing techniques. Remote sensing is a general term, which refers to non-contact techniques for data acquisition of targets or phenomena in real time or after recording by spacecraft, satellites, aircraft, buoy or ship, using imaging sensor technologies. Remote sensing techniques for icebergs detection and icebergs deterioration dynamics have been discussed in an abundant literature (Skolnik and Merrill, 1980, 2001; Benedict, 1972; Clay and Medwin, 1977; Robe *et al*, 1977; Gustajtis and Rossiter, 1979; Buckley *et al*., 1985; Newell, 1993; Davidson *et al*., 1997; Hoxtel and Miller, 1983; Canadian Seabed Research Ltd., 2000; PERD report 20 - 46 2000[4]; Dykstra, 2002; Le Chevalier, 2002). Remote sensing tools located on satellites are used to detect icebergs.

Environmental factors such as adverse sea conditions and weather will affect deployment options and overall functionality of any remote sensing sensor. The techniques employed for iceberg detection, location, morphology measurements and towing, drafting and decay of icebergs are classified such as:

- electromagnetic techniques: high frequency radar techniques - (300 MHz to 30 GHz) for radars using microwaves for ice dielectric properties measurements , with scatterometers and low frequency radar techniques (10 to 100 kHz), measuring the electrical conductivity of sea ice and water. Satellite altimetry is able to detect objects rising straight over the sea surface. The return echoes of the altimeter (or waveforms), have an earlier return of the

[4] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Max_draft_00.pdf

signal when there is something rising over the sea on which the radar beam can be reflected (Tournadre, *et al.*, 2008). Icebergs smaller than one km^2 are difficult to detect on a global scale using satellite mounted remote sensing technologies. Interference with clouds can make it difficult to detect small icebergs.

Radar is a key technique in most iceberg detection systems (Veitch and Daley, 2000). According to Wadhams (2009 n.p.):

> [t]he most useful type of sensor for detecting icebergs is the SAR - Synthetic Aperture Radar - which combines high resolution with day-and-night weather-independent capability. Remote sensing tools with a pixel size of about 20 m are capable of resolving most bergs. The new generation of SAR tools developed in the early 21st century, such as the Canadian RADARSAT and the European ENVISAT, are able to survey wide swaths (up to 400 km wide) in every orbit and are thus capable of surveying entire zones once per day.

Since 1998, C-CORE has conducted considerable research into the satellite detection of icebergs. Table 6.1 provides a summary of the research projects into the satellite radar detection of icebergs conducted between 1999 and 2006.

Table 6.1 Research Projects on Satellite Radar Detection of Icebergs (from PERD/CHC, 2007 n.p.)

Program	**Reference**	**Notes**
ADRO 1997/1998	Randell *et al*., 1999 and 2000	RADARSAT 1 fine mode iceberg detection - ground truthing off Newfoundland and Antarctica
ADRO 1999	Flett *et al*., 2000	RADARSAT 1 range of scansar and wide resolution modes - ground truthing off Newfoundland - some data on ship discrimination
ADRO -2, CIS 2000	Power *et al*., 2001	RADARSAT 1 range of scansar and wide resolution modes - ground truthing off Newfoundland - POD assessments based on wind speed and look angle
ADRO &CIS, ENVIRSAT 2003	Lane *et al*., 2003	RADARSAT 1 & ENVISAT POD assessment based on wind speed and look angle
CIS/IIMI 2003/2004	Howell *et al*., 2004 and 2006	RADARSAT 1 & ENVISAT effect of polarisation in ship/ ice discrimination
CIS GMES 2005	C-CORE, 2005b	ENVISAT ship - iceberg discrimination
Barents Sea 2003	C-CORE, 2006a	ENVISAT - Ground truth ship and icebergs - inexact ground truthing hence correlations uncertain

Wu *et al.* (2008) worked and detected the seasonal and geographical patterns of 8,000 icebergs in the Southern Ocean (Figure 6.2).

Figure 6.2 Antarctic Peninsula on March 8, 2006. Highly detailed image showing large icebergs of hundreds meters long, floating amid smaller pieces of ice (credit Formosat-2 Liu and Wu[5], 2008 n.p.)

- optical techniques: photography, video cameras, fluorescence line imager, compact airborne spectrographic imager (CASI), used by LANDSAT satellite series thematic mapper, NOAA satellite series or High Resolution visual Scanner (HRS). Techniques exist for detections above and under water line, under poor visibility and at night. According to AAD (n.d. n.p.):

> In the Antarctic, satellite images are used to track glaciers rifts tens and even hundreds of kilometres inland from the outer margin, and running parallel to the margin. These rifts typically develop and extend over many years till an iceberg breaks off.

Landsat imagery has been used to detect icebergs (Nazarov, 1962; Hult and Ostrander, 1974). Nazarov's (1962) map of iceberg sightings in the Southern Ocean revealed that icebergs form 'streams'. Using Landsat imagery, icebergs with a freeboard of about 700 m x 40 m x 40 m could be detected.

[5] http://earthobservatory.nasa.gov/IOTD/view.php?id=8604 see also http://www.ncku.edu.tw/~earth/people/liu/3.pdf

- acoustic techniques which for underwater applications employ ultrasound to determine the underwater iceberg profile (sonar). Acoustic techniques sonar profiling methods are used for the determination of icebergs characteristics. These techniques help to understand the process that result in icebergs melting and collecting of resulting melted freshwater. Figure 6.3 schematises the principle of acoustic technique (sonar) used to determine the underwater dimensions of icebergs (Hodgson *et al.*, 1988).

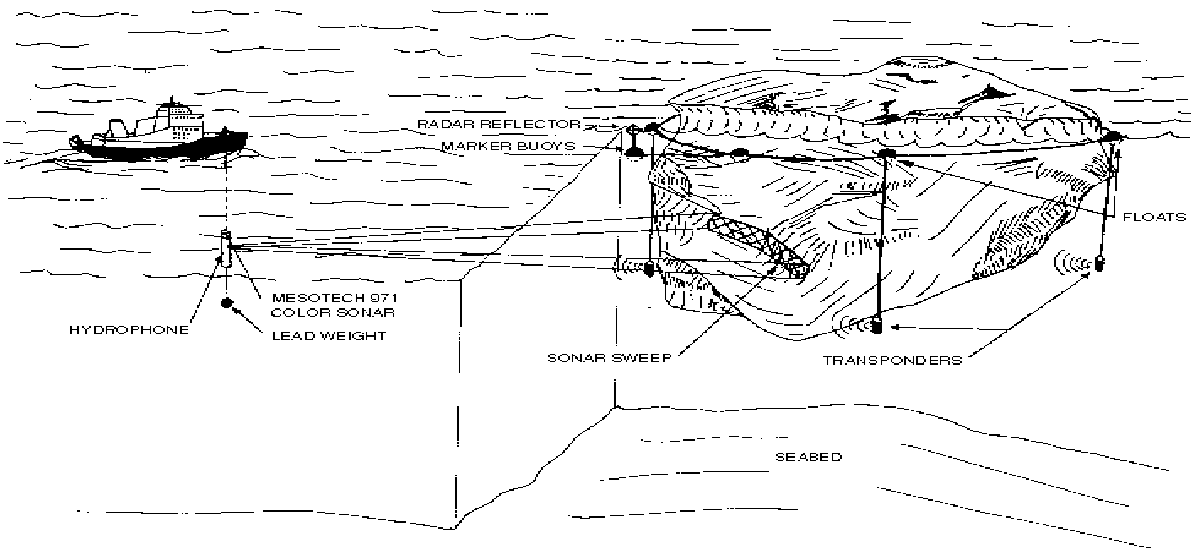


Figure 6.3 Schematics of the Principle of Acoustic Technique (sonar) Used to Determine the Underwater Dimensions of Icebergs (credit Hodgson *et. al.*, 1988 in Timco, 2000[6] p. 59)

Measurements of the above-water characteristics of an iceberg are undertaken as the iceberg is circumnavigated. These acoustic techniques can be used to select icebergs and measure the size of icebergs and to record deterioration during operation.

According to McKenna *et al.*, (2000 p. 65): "[L]inear dimensions are determined trigonometrically using the recorded ranges and angular dimensions". For below water measurements, Hodgson *et al.* (1988) conducted experiments for measurements of iceberg draft using sonar systems off the coast of Labrador (Figure 6.4).

6 ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Max_draft_00.pdf

Figure 6.4 Polarscan during the Mobile 1984 Iceberg Survey (credit Canadian seabed Research Ltd, 2000 p. 57[7])

In these experiments an iceberg was encircled with rope to which were attached four acoustic receiving transducers (transponders). The transponders, which received pulses emitted from an ultrasonic generator, were positioned at equal intervals and suspended around the iceberg at depths between 80 and 100 m. According to McKenna *et al.*, (2000 p. 58):

> The assembly collected range information from the acoustic transponders and determined the iceberg profile along the horizontal swath. A compass mounted in the scanning head the vessel provided an azimuth reference for the sonar data.

On completion of the horizontal profiles from one position, the vessel was moved to a station between another set of transponders, and profiling begun again, until data were collected from between all four transponder locations. Finally, a 3D image of the iceberg was obtained. From these experiments it was deduced that an average uncertainty of about 15% for iceberg underwater profile can be expected from this method (Hodgson *et al*., 1988). A number of operational problems were identified during the experiments, including:

- lassoing icebergs and deploying transponders are intricate and complex operations even in calm sea conditions;

[7] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Max_draft_00.pdf

- calving and rolling events required repositioning the transponders before profiling could begin again;
- the position of the transponders in relation to the iceberg could not be defined very accurately and the motion of the vessel, while trying to stay on stationary position produced a significant degradation in profile accuracy.

The complete survey of an iceberg using in acoustic field methods is a lengthy process. Canadian Seabed Research Ltd (2000) found that it took 10 daylight hours to complete the measurements. The duration of the experiment was influenced by: the size and the shape of the iceberg, the weather and sea conditions and the ability of the vessel to maintain its position relative to the iceberg throughout the survey. Numerical and experimental physical models of iceberg deterioration have been proposed in the last ten years (Veitch and Daley, 2000; Liang *et al*., 2001; Moores *et al*., 2001). These models have successfully integrated a number of critical factors responsible for iceberg deterioration, such as iceberg orientation, floatation, stability and mass evolution due to continuous melting and morphological changes. For precise details of iceberg shape and under water dimensions, an Autonomous Underwater Vehicles (Dhanak and Holappa, 1996) can be used to survey icebergs. According to Weeks (2011, communication) there are any realistic modeling of iceberg behavior during transport would flaws that control their strength under wave induced flexing. According to Fernandes *et al.*, (2003 p. 1): "[A]utonomous underwater vehicles (AUV) are unmanned submersibles that can be pre-programmed to navigate in three dimensions under water" (Figure 6.5).

Figure 6.5 Autonomous Underwater Vehicle - Autosub onboard RRS James Clark Ross (credit British Oceanographic Data Centre Natural Environment Research Council[8], 2010 n.p.)

[8] http://www.bodc.ac.uk/projects/uk/autosub/

According to Brandon and Banks (2006[9] p. 1):

> In 2001, an AUV, the *Autosub II*, was deployed at the north-west edge of the Weddell Sea as part of the Under Sea Ice and Pelagic Systems (USIPS) program. ... [the project had two main objectives:] to investigate the physical and biological environment of the Antarctic Marginal Ice Zone and to assess the potential of the AUV for improving acoustic estimate of biomass.

This AUV was equipped with a complex array of sensors and had 6.8 m long, 0.9 m diameter, 3,000 kg, endurance over 400 km at 1.7 m/s diving depth to 1600 m. During these campaigns, *Autosub II* observed 22 icebergs. Their drafts varied from 12 m to 146 m (Brandon and Banks, 2006). Spatial statistical methods were used in conjunction with the data obtained from the AUV survey to ascertain the likely distribution pattern of the icebergs in the area, and it was found that there is a particular type of distribution of iceberg in the region studied.

Table 6.2 synthesises the icebergs detection systems and the supporting platforms for icebergs detection, location, decay during drifting.

Table 6.2 Detection Systems and Supporting Platforms

Systems	**Vessel/ship**	**Autonomous underwater vehicle**	**Air craft and helicopter**	**Satellites**
Visual	X		X	
Radar	X		X	X
Infrared	X	X	X	
Optical	X		X	X
Acoustic- Sonar	X	X		

6.1.1 Discussion

Remote sensing technologies underpin safety and efficiency issues for icebergs management planning and operations for icebergs and resulting melting freshwater transportation, such as:

[9] http://adsabs.harvard.edu/abs/2006AGUFM.C41B0323B

- ship based observations near the zone of iceberg capture. They include the deployment of autonomous observation stations fitted with sensors linked to an ARGOS satellite for information on strain and tilt, atmospheric pressure, positioning. The ARGOS satellite system for environmental data which operates from both fixed and mobile platforms over the world;
- satellite image data analysis (Envisat, Radarsat, ALOS) at different spatial resolutions with a “pattern-recognition algorithm” to detect and select small icebergs. According to McKenna *et al.* (2004 n.p.):

> Radar imagery could be used to monitor the physical changes in icebergs, such as surface melting. Estimates of the freshwater flux could be made by combining size information from satellite imagery with freeboard elevation from satellite altimetry (ICESat, CryoSat, Envirsat), and both could be compared with modelled melt rates.

The technological advancements of remote sensing for iceberg detection and selection can successfully supply information on the location, shape, size, environment, and stability characteristics of icebergs with high levels of accuracy allowing iceberg selection and management. However to determine tabular icebergs dimensions large-scale draft measurements are sufficient (Weeks, 2011 personal communication).

6.2 Iceberg Selection Process

A wide range of techniques allow for assessing the parameters concerning the locations of the resources, the volumes and shapes, the oceanic conditions and the currents, the deteriorations of icebergs and the environmental impacts. The selection of the iceberg is undertaken considering the accessibility to the site and iceberg stability. To secure the transporting operations, iceberg should be selected using specific criteria (Smakhtin *et al.,* 2001):

- physical characteristics of the iceberg selected for transportation, including its type, shape and size. The shape is related to the stability, the size to the water volume at the destination;
- icebergs life duration estimation is critical in order to quantify the volume of water delivered at the destination site. The iceberg must remain stable during its melting voyage for six to twelve months depending on its size;
- trajectories of icebergs and risks of collision with other icebergs and frequent boat trips;

- meteorological data, such as the direction of prevailing winds, atmospheric pressure, isolines which can predict fog probability, storms and cyclones, currents and their periodicity which are related to transportation;
- regional environmental situation within which an iceberg transportation system would operate. Temperature variations of local sea water could be in the order of 10°C and of the air greater than 25°C, which can affect local temperatures and local marine organisms.

6.2.1 Operational Selection

Iceberg sizes can be determined with operations performed via remote sensing techniques (SAR, Sonar) (Williams and Rees, 1999; Lane *et al*., 2002). The IIP in Newfoundland developed a methodology to detect specific icebergs from iceberg distributions in a particular geographic region using satellite data (Gladstone and Bigg, 2002). It consists of designing several zones with different criteria and to undertake progressively a precise selection: for example, in the 'Confirmation Zone' icebergs physical characteristics are detected and in the 'Tracking Zone' the drift tracks of icebergs are evaluated from the exact location of the icebergs by a computer system. Detailed icebergs tracks are established while the icebergs are still far enough away (20 to 30 miles and 24 - 72 hours). According to the Iceberg Management Procedures suggested by the IIP, a daily survey of icebergs provides information that can be used to ascertain the directions in which icebergs are drifting and are likely to drift in the future. The 'tactical zone' constitutes the environment within which the C-CORE and the IIP towed icebergs. They had to negotiate a range of hazards (such as other icebergs) while undertaking towing operations for this purpose. The size, the position and the drift speed of an iceberg are estimated precisely. In Canada, Provincial Aerospace Ltd[10] is also involved in management of planning maritime operations in the Grand Banks. In each spring season general area for icebergs presence is determined (PERD/CHC, 2007). Figure 6.6 shows sighting drift history (51° N - 46° N) of a tabular iceberg in 2002 in Canada. The same remote sensing techniques and procedures are currently undertaken in Antarctica (See Coleman, 2003[11] for the Amery Ice Shelf) and work with the same range of surveying practices and a focus on iceberg transportation projects could provide useful detailed information.

[10] Environmental Service Division http://wwww.provincialaerospace.com/
[11] http://www.antarctica.gov.au/__data/assets/pdf_file/0018/22284/ml_378866908564815_loosetooth.pdf

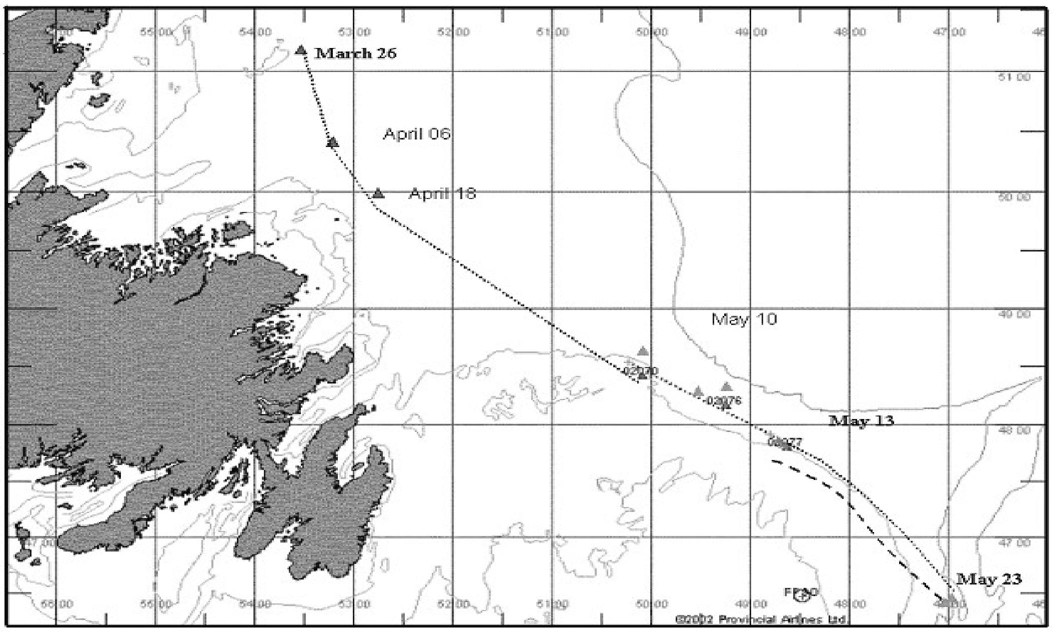


Figure 6.6 Drift History (51° N - 46° N) of a Tabular Iceberg in 2002 (credit Scott *et al.*[12], 2010 n.p.)

Table 6.3 gives details for ice season 2002 in East Cost of Canada detected by different techniques of icebergs of different sizes and shapes emerged from the sea and arrived by waves as a hundred in the same time.

Table 6.3 Evolution of icebergs in spring ice season in 2002 in East Cost of Canada (data from Scott *et al.*, 2003 n.p.)

Date	Sighting source	Size	Side-Scar Sonar
26 Mar	Dept of Fishery and Oceans Canada	7 km long	
06 April	Dept of Fishery and Oceans Canada	2 km long	
18 April	Dept of Fishery and Oceans Canada	1.8 km long	
10 May	Provincial Airlines Limited - ice flight	1…2 km long	
13 May	Provincial Airlines Limited - ice flight	500 m long, 200 m wide 200 m long, 100 m wide	12.5 Million t 1.3 Million t
23 May	Vessel	2 large pieces	
27 May	National ice Centre	612 m long, 420 m wide 222 m long, 137 m wide	30 Million t 2.5 Million t

[12] www.vos.noaa.gov/MWL/fall_03/icebergs.shtml and www.vos.noaa.gov/MWL/Images/iceberg_fig1.jpg

Currently it is in Canada that exists the most advanced operational detection techniques. Iceberg resources operations are well documented and experimented in Canada and allow different levels of detection accuracy (Veitch and Daley, 2000[13]; C-CORE, 2002[14]). This information could be used in case of iceberg transportation projects to manage the transportation systems. The results of these zone definitions could be evaluated for an iceberg transportation system through more sepcifically environmental assessment measures. The sites of iceberg utilisation would have to be chosen considering the limiting obligations to respect the characteristics of their ecosystems. Similar detection process could be applied to carry on an iceberg survey in a region between the Amery shlef and WA.

6.2.2 Operational Selection of Icebergs

The properties of the iceberg resource and its location determine the range of transportation operations available: the selection criteria and the techniques to harvest icebergs and the techniques to transport them have been studied in past projects. Many scholars, such as: Merrill (1966), Fitch and Jones (1973), Weeks and Campbell (1982), Hult and Ostrander (1982), Victor (1982), Connell (1982), Smith (1986), Page (1986), Mamo (1982), Sobinger (2004) and Shick (2004) have given details on how icebergs can be chosen and how they can be selected. The results of their studies in terms of their estimation of iceberg selection are consistent. Icebergs are enormous and their sheer size represents a significant challenge for any transportation system. In Antarctica, there is an abundance of differently sized and shaped icebergs. According to Hult and Ostrander (1973), the annual yield of iceberg could be about 1,200 km^3 and the total accumulation in the Antarctic Ocean about 7,000 km^3. Estimates of iceberg annual production from Hult and Ostrander (1973) are given in Appendix 3.

However, icebergs suitable for transportation projects need to be of a thickness (greater than 250 m) that will ensure that the iceberg does not break up/melt too quickly (Smakhtin *et al.,* 2001). While many different types of icebergs exist and could be transported, the studies noted above have suggested that small and medium sized tabular icebergs are most easily captured and transported (Bigg *et al.*, 1997). Broadly, they all conclude that tabular icebergs, of various sizes, are the most suitable for iceberg harvesting and transportation stability. The thickness of tabular icebergs is typically about 700 m at the landward edge to about 250 m at

[13] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Iceberg_evol_00.pdf
[14] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Greenland_02.pdf

the seaward front (Quilty, 2003). Tabular icebergs combine a relatively good stability with a large volume of water, mineral integrity (Walton, 1987). In the projects described previously and directed towards the movement of icebergs, the focus of operations has been on maritime engineering. Quilty (2003 and 2006) has determined that icebergs of around 1 million t are the minimal size that could be profitably transported. Quilty (2003) specified that the size of an optimal iceberg at an operational stage would measure about 0.04 km^3 and weigh about 36 million t, which is about 300 m by 600 m in area, with a depth under the water of about 200 m. Quilty (2001 n.p.[15]) compared the operational task of wrapping such an iceberg with that of protecting a cricket ground from rain:

> But with all that iceberg surface area, it is only about 40 times the area of the MCG (Melbourne Cricket Ground), and so if they can cover the MCG fairly quickly in case of rain, I suspect a couple of decent trawler operators could lead this lot under an iceberg and start the wrapping process fairly readily.

In Antarctica, the Ross and Filchner ice shelves, covering an area of about 10^6 km^2, produce tabular icebergs (Schwerdtfeger, 1985). Figure 6.7, Figure 6.8 and Figure 6.9 show tabular icebergs in Antarctica which would correspond to iceberg transportation projects average and large scales targets (Chapter 7).

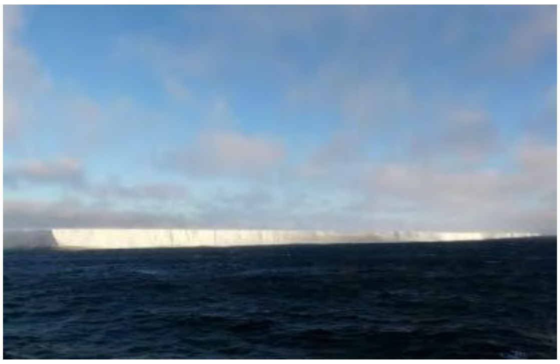


Figure 6.7 Iceberg C-18A Formed in Ross Sea Shelf in 2003, 18 km long and 6 km wide (credit Chakos, MBARI[16], 2003 n.p.)

[15] http://webcache.googleusercontent.com/search?q=cache:SL_NrasVa_wJ:www.abc.net.au/news/features/antarctica/+quilty+iceberg+surface+area+it+is+only&cd=1&hl=en&ct=clnk&gl=au
http://www.farmhand.org.au/downloads/82-93_Producing_more_%20water_Part_8.pdf, Mansfield *et al.,* p. 90

[16] http://icestories.exploratorium.edu/dispatches/our-first-iceberg/

Figure 6.8 Iceberg, B-15A 160 km long, 70 km wide, Drygalski Ice Tongue (credit ESA[17], 2005 n.p.)

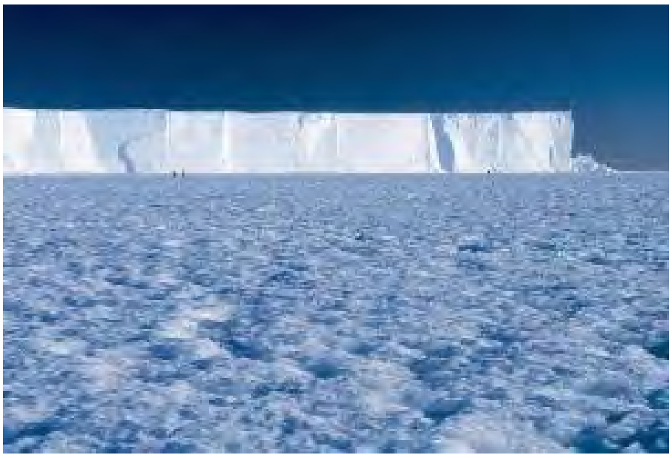


Figure 6.9 Iceberg B-15A Grounded at Cape Washington in the Ross Sea (credit Van Woert, NOAA[18], 1997 n.p.)

6.3 Operational Icebergs Management

Hult and Ostrander (1978), Mougin (1980), Connell (1982), Sobinger (1986) and Abramovitch (2004) all designed methods by which to approach an iceberg and to handle it

[17] http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=14361
[18] www.ens-newswire.com/ens/pics22/iceberg.jpg

efficiently. However these handling methods were not tested in-situ on large icebergs. For transportation operations, the stability of an iceberg and, in particular, the effects of melting on iceberg stability and the sailing conditions represent major obstacles to iceberg handling and determine the types of harnessing techniques which could be effectively used (Chirive and Miller, 1978; Huppert and Turner, 1978; Mellor, 1978; Cluff, 1979; Robe, 1979; Russell, 1979; Smith, 1979). It is therefore important to forecast the iceberg deterioration and the climatic conditions for operational and transportation purposes. C-CORE techniques represent a benchmark in this area.

6.3.1 Harnessing Icebergs

Harnessing icebergs is a crucial aspect of iceberg transportation (C-CORE, 2001a; 2001b; 2002; 2003a; 2004a; 2005a; 2005b; 2005c). Harnessing decision is influenced by the following factors: iceberg location, confidence in iceberg detection, features of the iceberg (size, mass and shape), towing resource (location, availability, capacity), and meteorological conditions. It was already established that ideal harnessing conditions require relatively calm maritime conditions.

C-CORE (2004) suggested that the best methods for harnessing icebergs is to surround icebergs with a network of steel cables below the centre of mass as shown in Figures 6.10 and 6.11.

Figure 6.10 Single Towline Slipped over the Iceberg, Program of Energy Research and Development Canadian Hydraulics Centre (credit PERD/CHC, Report 20-84, 2007 p. 50)

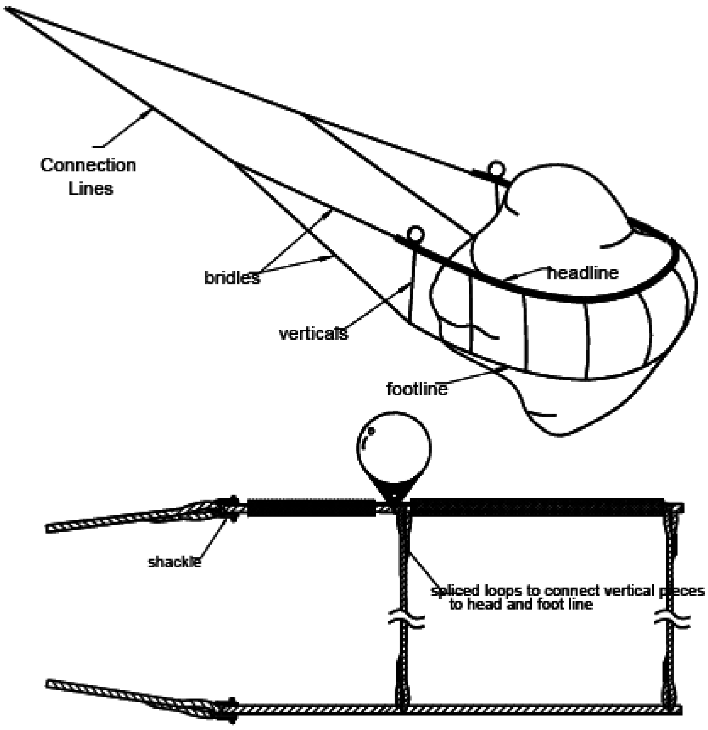


Figure 6.11 Iceberg Net Towing (credit PERD/CHC, Report 20-84, 2007 p. 49)

Iceberg harnessing is a process that consists of a number of specific operations:

- passing a tow wire around the iceberg;
- activating a system to recover the towline in the case of an iceberg breaking;
- wrapping the iceberg with a long cable;
- harnessing the iceberg by means of a large shackle to a towing tug.

For successful towing operation several key features were designed effectively harnessing and towing icebergs:

- specific length of the net depending on each iceberg size and shape, to avoid the slipping underneath after several hours of towing;
- improvement bridle design to prevent the collapsing of the net;
- simple configuration and assembly of the net to facilitate repairs at sea if necessary;
- enhanced handling through use of a purpose-built storage reel (Figure 6.12);
- if necessary easy disconnection of the towing vessel from the iceberg and evaluate alternative management scenarios.

Figure 6.12 Iceberg Net Storage (credit PERD/CHC, Report 20-84, 2007 p. 50)

Different types of material and process have been developed by the C-CORE in the years 2000s such as buoy, beacons, transponders, webs, dual vessel towing techniques, (Figure 13.a)

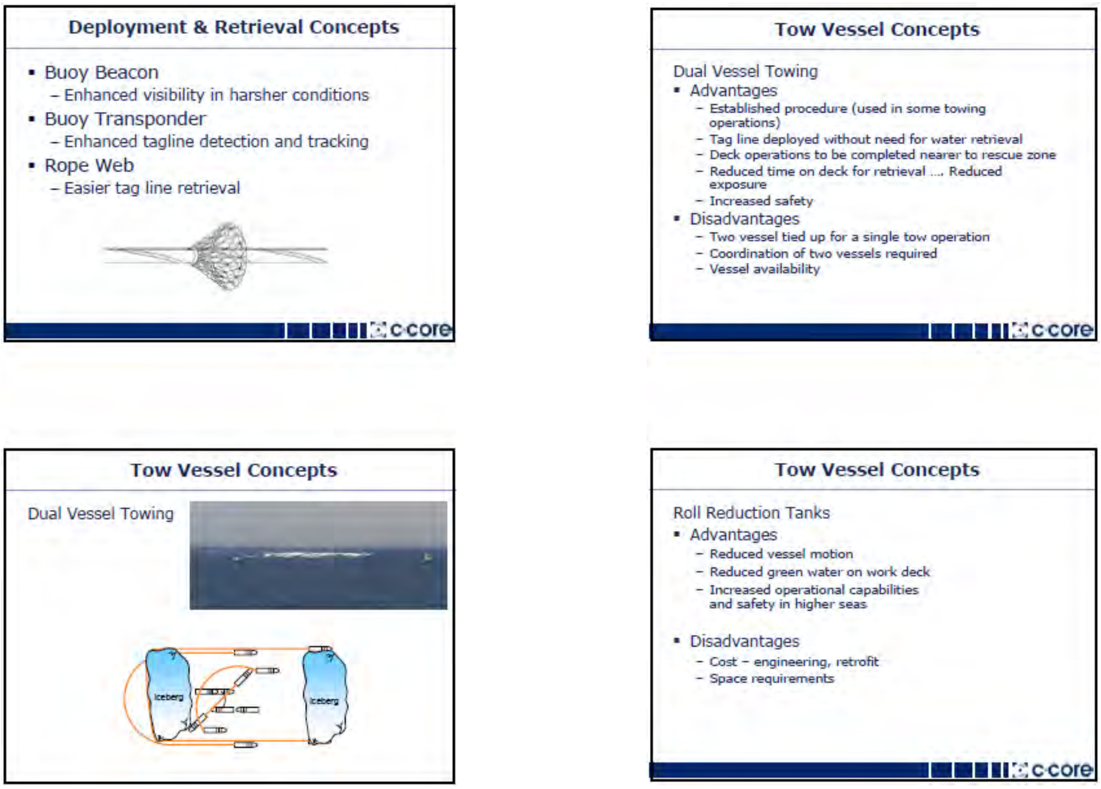


Figure 6.13a Two Vessels Towing (credit PERD/CHC, 2007 p.[19])

[19] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/2_Ice-Structure_Interaction_06.pdf

Modern management techniques are used to deflect large icebergs, such as:

- single vessel towing, to deflect small masses of less than 100,000 t (icebergs of 50 to 100 m long);
- dual vessel towing, to deflect masses larger than 1,000,000 t (> 200 m long).

Figure 6.13b shows the procedure used by a single vessel for iceberg towing, which is standard practice in iceberg management (PERD/CHC Report 20 - 84, 2007).

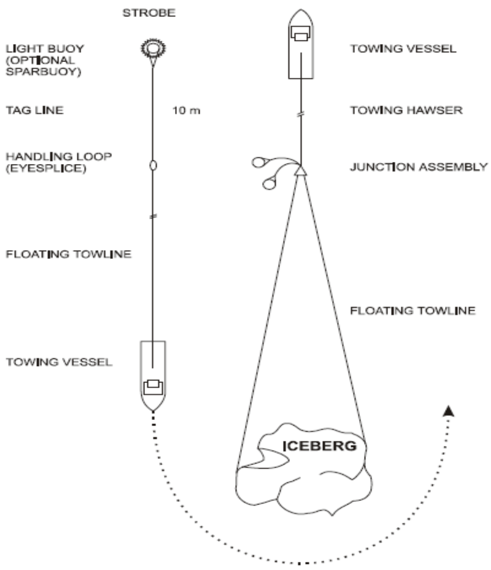


Figure 6.13b Single Vessel Towing (credit PERD/CHC, Report 20 - 84, 2007 p. 27)

In many icebergs the mechanical action of waves creates a waterline groove which can be used to catch and secure a hawser (thick towline) (Veitch *et al.*, 2001). This reduces the rolling movement of the iceberg from a given tow force. In this case, towing catenaries are used to reduce the unstable iceberg overturning movement (Figure 6.13c and Figure 6.14).

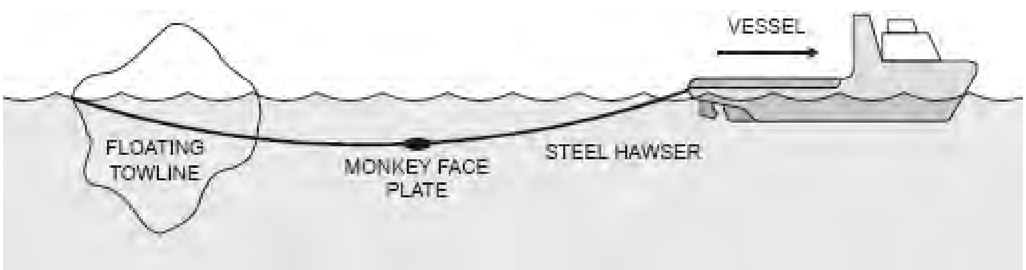


Figure 6.13c Single Vessel and Towing Catenaries to Reduce Overturning Moment of Unstable Iceberg (credit PERD/CHC, Report 20 - 84 2007 p. 26)

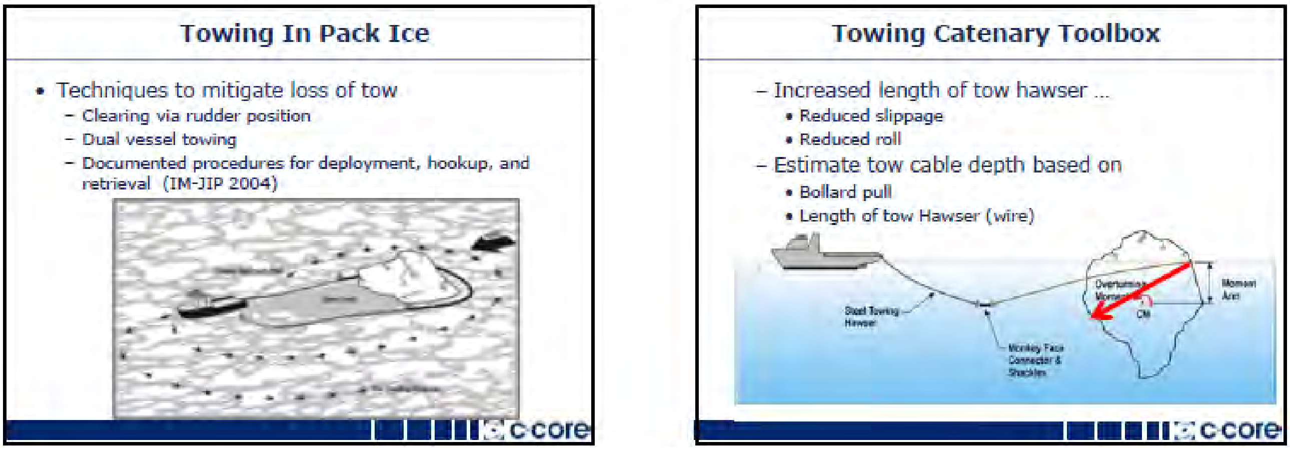


Figure 6.14 Single Vessel Towing (credit PERD/CHC, 2007 p.[20])

According to McKenna *et al.*, (2007 p. 28) to move larger or unstable icebergs:

> Towing is conducted with two vessels to deflect larger or unstable ice masses. The approach requires two vessels, a single wire rope, and one steel hawser for each vessel. The approach is practical and can produce a significantly greater tow force; however, there can be difficulties in having a balanced vessel thrust, a tendency to see-saw around the iceberg while towing, and difficulty in maintaining depth control over the tow wire. (PERD/CHC Report 20 - 84, 2007).

For larger icebergs up to four vessel arrangements can be designed (Figure 6.15).

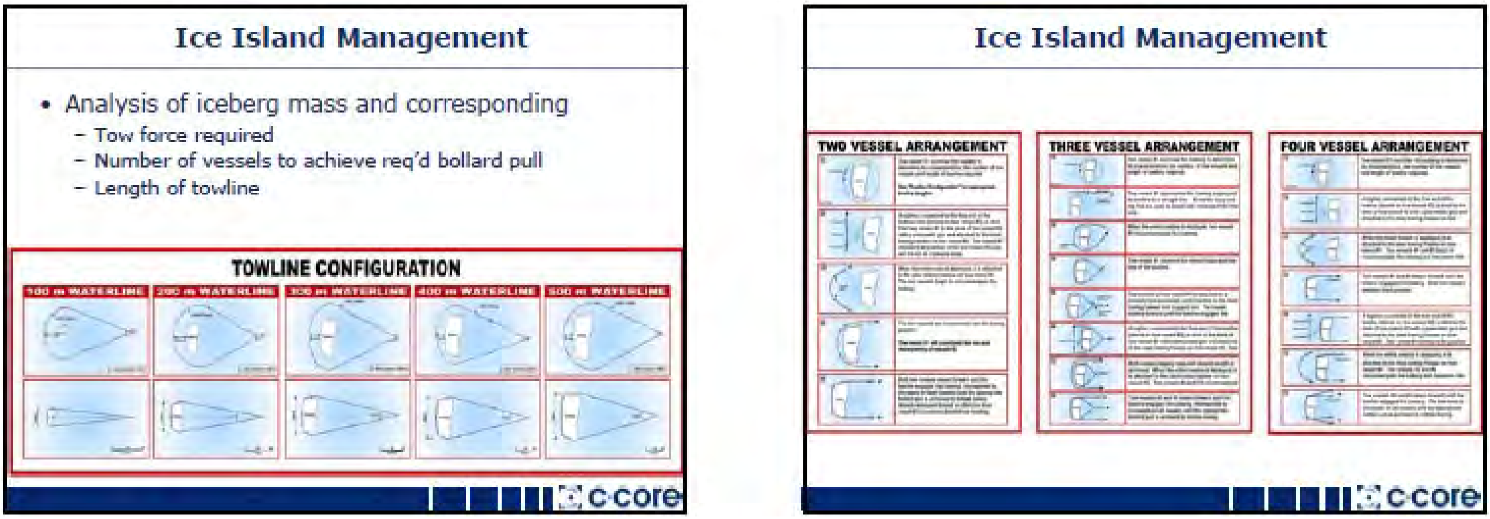


Figure 6.15 Towing Configuration (credit PERD/CHC, 2007 p.[21])

[20] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/2_Ice-Structure_Interaction_06.pdf
[21] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/2_Ice-Structure_Interaction_06.pdf

Iceberg harnessing is a very difficult task for towing effectiveness and all the processes have to be undertaken with a great deal of caution, requiring skilled vessel handling. The buoyancy forces and the gravity forces lead to large scale fractures of an iceberg. In the Southern Ocean, winter storms with winds up to 130 km/h can produce 30 m high waves (McKnight *et al.*, 2000). Icebergs undergoing transportation are largely unaffected by the effects upon the sea of earthquakes and other natural disasters such as tsunamis. Hult and Ostrander (1973) reports that 250 m deep icebergs are not affected by 30m high sea waves.

6.3.2 Iceberg Deterioration

Landsat data suggested that many icebergs break into two almost equal parts, after escaping from the relative protection afforded by pack ice. Smaller icebergs are more unstable and ultimately overturn, which accelerates their decay. Iceberg deterioration depends on drag, strength and thickness of crevasses. During iceberg transportation, the heat transfer by convection usually takes place below the surface of the iceberg. The non-uniform surface thickness of an iceberg favours ablation, which determines iceberg instability. A significant risk associated with iceberg transportation is the calving due to wave erosion and temperature gradient and the breaking into a number of pieces which roll over after they drop into the sea. Therefore, iceberg stability is a critical technical parameter for any towing operation. The physical behaviour of large icebergs during transportation could be modelled with specific information on crevasse spacing, the effects of wave erosion and basal melting. Developing performant modelling could allow analysing with correlation of the modelling results the potential melting and the collection of freshwater by image acquisition. In 2010 the 3DS team undertook a digital simulation of a new iceberg transportation project from Mougin. The CATIA software and the SIMULIA Abaqus software allowed to assess the interactions between the iceberg, and its transportation system and the potential environmental impacts of an iceberg breakage, reproducing the ocean conditions, the speed and temperature of the sea currents and winds (3DS, 2010[22]).

6.3.3 Sailing Conditions

Iceberg resources are located in Polar maritime regions (10% in the Northern Hemisphere and 90% in Antarctica) and are far away from sites where freshwater is highly demanded as for example from Alaska to south-western States of the USA and Mexico (Davidge, 1994) or

[22] http://perspectives.3ds.com/environment/how-to-tow-an-iceberg-pt-1/

from Antarctica to South Africa or Australia (Job, 1978; Mellor, 1980). The icebergs drifts within the maritime space often interfere with the natural existing maritime routes. Iceberg transportation projects forecasted the use of the same maritime transportation systems and patterns as those currently used by regional shipping lines, related to frequent boat trips. However, because icebergs are located many thousands of kilometres away from potential consumers, the transportation systems for steering icebergs in a specific direction are limited by the extreme climatic conditions existing in these high latitudes and by the cost of energy required to shift icebergs across vast distances. Maritime environment components (state of the sea, extremely strong winds, fog, ocean waves, and seasons) determine the characteristics of any iceberg transportation system. These components can create serious hazardous conditions for transportation. The physical environment of icebergs becomes extreme in winter. Days have very little light, and there are low temperatures, ice conditions, extreme winds, and fog. Poor visibility due to fog, low clouds, rain and snow are also common occurrences in rough sea conditions and will have a significant influence on the effectiveness on remote sensing techniques. The accessibility to the iceberg resource is therefore limited by these climatic factors and restrains the schedule of the transportation system to warmer Antarctic summer months. These extreme climatic conditions represent a major challenge for any maritime transportation system. During break-up and freeze-up, sailing conditions are particularly dangerous. The most violent storms in Antarctica blow in spring and in autumn, with winds howling at force 9[23]. The iceberg transportation operation involving deployment of the facilities would not be practical in winter such as iceberg harnessing. On a relatively small scale, 100,000 t icebergs have been towed successfully (Quilty, 2001). Sobinger (1986) successfully demonstrated that it is possible to tow 300,000 t icebergs but these operation were able to be performed only in relatively calm maritime conditions, which occur more often in summer. However, the obstacles represented by the harsh maritime conditions can also be considered as a unique advantage for Polar transportation systems and the strong winds, together with the powerful maritime currents, could be employed as a motion force to assist in the transportation of the icebergs water if a semi automatic system could be designed.

Iceberg drift velocities need to be monitored in order to steer it. The motion of an iceberg depends on winds, currents, and the underwater characteristics of the iceberg. Maritime environment components are also important to assess the economical feasibility for a transportation system. Depending on the climatic conditions and the sea state, several

[23] www.weatheronline.co.uk/.../Antarctica.htm

techniques are available to monitor iceberg deterioration and the sailing conditions. These remote sensing techniques could secure specific operation, which would not involve the deployment of large infrastructures, such as pure transportation using winds and currents.

Maritime transportation using natural driving forces, ocean current and winds could be the most appropriate system to transport icebergs: it would decrease the costs of iceberg water transportation and would minimise the amount of operations required to transport icebergs. Indeed, presently, the technological advancements of remote sensing, could allow to optimise the routing for individual icebergs (travel trajectories and duration) and efficient utilisation of new alternative energy sources produced by the natural driving forces (ocean, currents and winds) for icebergs transportation. The procedures used to tow the iceberg and the effectiveness of the operation would also require continuous evaluation. Modelling could provide information on simulated paths of iceberg drift. In calm maritime conditions, it was found that on average an iceberg could be towed for 10 hours at an average drift speed of 0.5 m/s (180 m/hour) over a distance of 20 km. (PERD/CHC Report 20-84). These conditions are likely to be experienced in the vicinity of locations in summer the AAT where icebergs would be sourced from meaning that the initial speed that a harnessed iceberg could be moved would be limited to similar speeds.

6.3.4 Risks Associated with Harnessing Icebergs

The main risks associated with the effects of Polar maritime conditions upon an iceberg under tow relate to the possibility of the iceberg breaking up and capsizing and overturning. This could damage the tug or the other transportation infrastructure (PERD/CHC Report 20-84 2007). An ever-present fog can reduce visibility to zero for days. The phenomenon of erosion induced by the sea waves at the water line of an iceberg produces protruding underwater rams and cantilevered shelves above water. Therefore the dangers for an iceberg transportation project are the risks represented by the collision among icebergs. In bad sailing conditions, one significant danger that needs to be addressed is the possibility of collisions between icebergs and icebergs and vessels. Veitch and Daley (2000) studied the risk of icebergs impact on fixed or floating installations, or conventional ship navigation, sub-sea installations, and pipelines in Canada. They have undertaken extensive studies related to the modelling of icebergs shape and size evolution (see Appendix 4).

Icebergs can be continuously detected with marine radar and discontinuously with airborne, satellite and ships. These remote sensing systems can assist in minimising the risk of a collision, excessive wear on vessel machinery and high fuel consumption for the vessel master. Another danger lies in the requirement to carefully navigate an iceberg under tow around and away from regions where large icebergs threaten to collide with the transportation system. One other method for mitigating this danger is the possibility advanced by Rudkin and Dugal (2001) of towing threatening icebergs away from the path of a transported iceberg. A ship operating in the vicinity of a large iceberg could steer to avoid a large parent berg, but it may consequently be also at risk from undetected close small icebergs. Small icebergs, and growlers from 120 t to 5,400 t, may damage ships. In order to control the direction of an iceberg, a range of specific techniques has been developed for the deflection of an iceberg. The standard deflection techniques for small icebergs are water cannon and propeller washing techniques. In the case of the former, water cannons (Figure 6.16a) are mounted on the superstructure of the vessel directing a high pressure steam of sea water to deflect iceberg fragments of up to 40,000 t, and in 7 m combined seas and 30 knot winds (PERD/CHC Report 20 - 84, 2007).

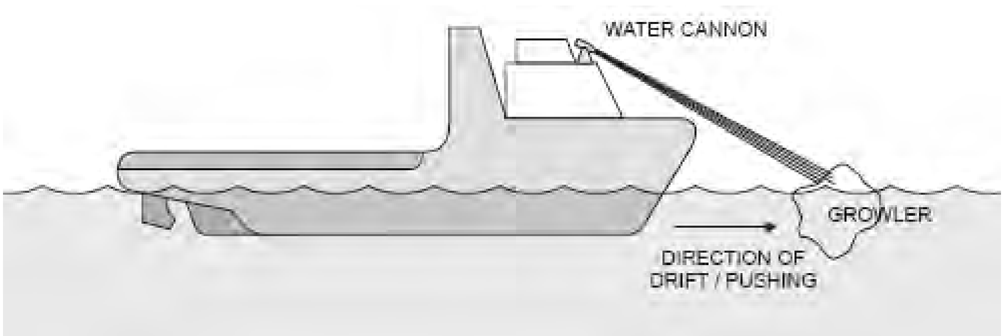


Figure 6.16a Water Cannon (credit PERD/CHC, Report 20 - 84 2007 p. 26)

The vessel is supplied with 3600 m^3/h of water ejected at a speed of 54 m/s. The cannons are mounted on the bow of the boat so that the boat can be manoeuvred more easily and safely. The technique for deflecting icebergs known as propeller-washing is used for small ice mass deflection. The forward motion of the vessel could act to brace the force of the cannons; it is safer to meet the likely backwash that could eventuate from an iceberg being moved (which can capsize, for example) on the bow of a boat than over the stern, which could swamp motors. This position also reduces vessel-icing potential during operations. It is an arduous task for the vessel master, requires high fuel consumption and exerts excessive wear on vessel machinery (Figure 6.16b).

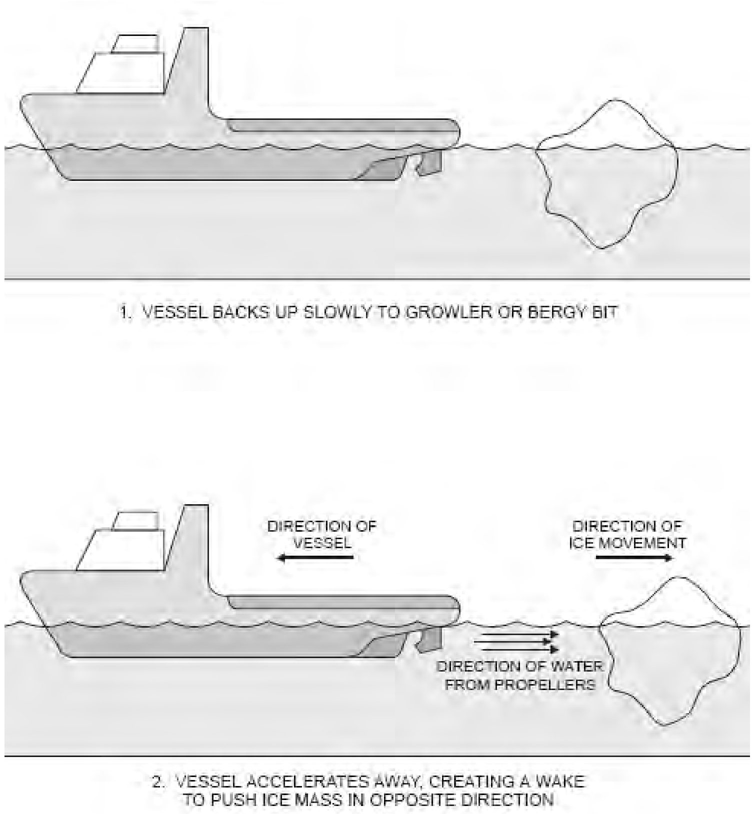


Figure 6.16b Propeller Washing (credit PERD/CHC, Report 20 - 84 2007 p. 31)

However, the presence of sea ice limits the capability of the propeller washing as a technique for shifting ice fragment as bergy bits and growlers.

The techniques developed, implemented and refined by the C-CORE offer the safest means to harvest, handle and transport icebergs (PERD/CHC Report 20 - 84). These harnessing techniques could be implemented effectively to deflect tabular icebergs for an operation of tabular icebergs from the AAT to WA. To fulfil one of the objectives of this thesis (related to collecting and transporting melted freshwater from the AAT to WA and using icebergs drift), the operating technique described in this section could be used for giving directions to bagged icebergs. The icebergs would then be melted and the melted freshwater would be transported in bags. This would offer the potential of “revolutionising” the transportation of icebergs for fresh water consumption. Novel forms of sailing propulsion, and in particular kites and sails, have also been developed and some of these are potentially applicable to bulk commodity transportation, such as icebergs (Spragg, 2004; Breukels and Ockels, 2007). These technologies will be presented now.

6.4 Waterbag Technology for Melted Fresh Water Transportation

The advent of new industrial materials used in transportation packing has been applied to the design of giant waterbags for freshwater transportation that are towed behind ships (Nordic Water Supply[24]). Figure 6.17a, b, c and d shows a bag used for water transportation being operated by Nordic Water Supply.

Figure 6.17a Giant Waterbag, Scale 1:20,000 (credit Nordic Water Supply, 2006 p. 5)

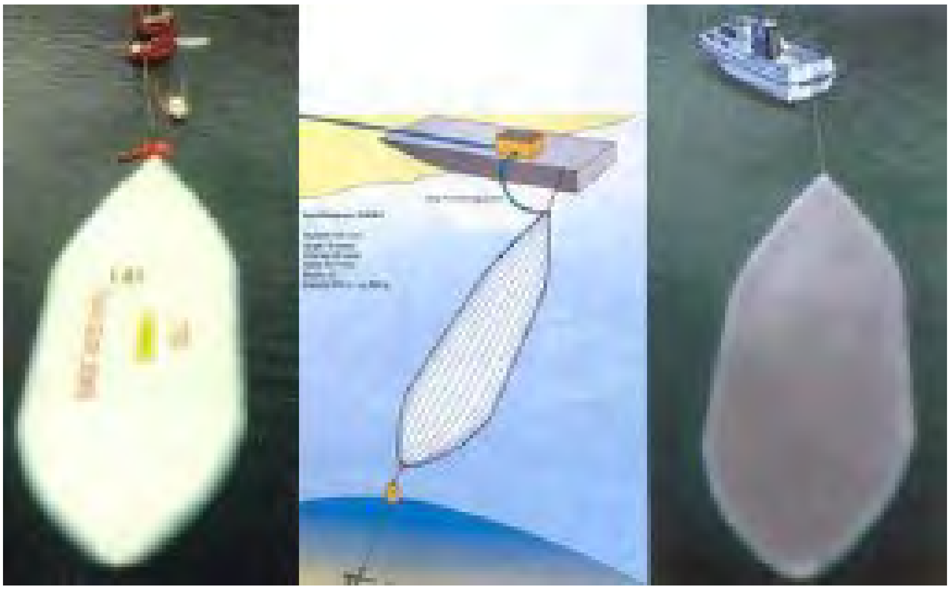


Figure 6.17b, c and d Real Image (left) and Sketches of Waterbag Scale 1:20,000 (credit NWS[25], 2006 n.p.)

[24] http://investing.businessweek.com/research/stocks/private/snapshot.asp?privcapId=4509140
[25] http://www.alshindagah.com/janfeb2002/Water_transport.html

A significant difficulty in using ships to transport icebergs is that a method of dealing with the melt water from an iceberg under long-distance transportation needs to be developed to minimise the loss of freshwater. At the turn of the 20th century, there has been renewed interest in an alternative to tankers transportation to freshwater shipping transportation technology using waterbags (OECD, 1999). Modern waterbag transportation is a fascinating version of an idea first described by Barnes Wallis in the 1930s. At the end of the Second World War, small types of rubber bags were designed and used by the US Army[26]. At that time, these bags were less costly than tankers for the transportation of freshwater and less detectable by radars. The bags had nearly the same density as sea water, but proved to be very unstable during transportation. During the last decades of the 20th century, a number of technological advances have seen a continuous improvement in transportation efficiency of waterbags. New types of waterbags were proposed by different specialised companies. There are significant advantages to waterbag transportation; for an equivalent amount of water transported, the bag itself weighs less than 1/6th the weight of an equivalent sized tankers transported volume. Waterbags are designed for bulk liquid transportation. The water volume transported is adaptable to the market, sanitary and security requirements, and flexible, depending on bags number (OECD, 1999). The bags used for oceanic transportation of freshwater will be discussed in that follows. I will examine these new types of waterbags and their systems below and assess how they could be used for iceberg water transportation.

6.4.1 Specialised Companies in Waterbag Transportation

In 2007, at least five corporations had developed waterbag technologies:

a. Aquarius Water Trading and Transportation Ltd., a British company;
b. Nordic Water Supply Company in Oslo, linked with NYK Nippon Yusen Kaisha;
c. Medusa Corporation, Calgary, Alberta, Canada, linked with MH Waters;
d. Spragg and Associates, Washington State, California (with CH2M-HILL, US);
e. Fabric Solution Australia and Solartran Australia.

An analysis of each of these five corporations is now presented in order to identify the elements, which could be involved in my thesis project of icebergs transportation feasibility from the AAT to WA.

[26] www.history.navy.mil

a. *Aquarius Water Trading and Transportation Ltd.*

Aquarius Holdings Ltd. is a British-based company funded by corporations such as Shell, Lyonnaise des Eaux and subsidiaries of the Northumbrian Water Company[27]. Aquarius developed a sustainable low cost water transportation system using flexible polyurethane bags[28]. The bags are built in England (Southampton) and tested by independent institutions and laboratories. The bags are patented by the National Sanitation Foundation (NSF) USA and their use is regulated by the International Standard Office (ISO 14000). Aquarius rent boats and operates eight bags with a capacity ranging from 720 to 2,000 t. In 1992 Aquarius Water Trading and Transportation became the first company to tow bags of freshwater for export. In 1997, Aquarius began to transport around 1 million m^3/year of water to the Greek islands, to the north-east islands of the Aegean Sea and 2,000 t to the Cyclades islands. Aquarius delivered commercial bulk quantities of freshwater to the Greek Islands of the Agean Sea sourced from Turkey, a journey of about 100 to 200 km [29]. The market for water transportation to the Greek Islands has been estimated to be around 200 million t/year. Tugs were used to tow the bags between loading and offloading sites. The company operates from the Piraeus Harbour. The waterbags transportation technology is clean as it consumes a small amount of fuel compared to the transportation of the same amount of water by boat. Aquarius waterbags loading and offloading process is fast, flexible, cheap and simple. Aquarius Water Trading and Transportation Company attempted to design larger bags of up to 20,000 t, for water deliveries to islands in the Mediterranean, Israel, the Bahamas and other islands in the Caribbean. Bags of this size could suit operation of volumes corresponding to the volumes of water of a 0.2 km^3 iceberg.

b. Nordic Water Supply (NWS)

NWS[30] is a company based in Oslo, Norway, that began as a group of Norwegian ship companies interested in pursuing economic opportunities associated with water transportation. Since 1997, NWS has operated out of Cyprus. In October 1997, the Government of Turkey contracted NWS to deliver seven million m^3 of water from Anatolia, Turkey, to north of Cyprus, using 200 m long bags with a capacity of 35,000 m^3.

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[27] www.aqvariusholding.com link is unavailable as the company doesn't exist anymore
[28] www.aqvariusholding.com link is unavailable as the company doesn't exist anymore
[29] http://www.tve.org/ho/series2/waterways_reports/watercigars_greece.html
[30] http://investing.businessweek.com/research/stocks/private/snapshot.asp?privcapId=4509140

To improve transportation in various climatic conditions NWS has developed waterbags made out of new materials, such as waterproof polymers, which are ultraviolet-proof and biodegradable. In 2000, NWS developed a 20,000 t waterbag and they have plans to produce larger bags that are 350 m long with a capacity of 100,000 m^3. Recently NWS cooperated with the Japanese shipping company NYK and some Middle East companies for freshwater transportation by bags. Figure 6.18 illustrate the Japanese solution for towage proposed by the Monohakobi Institute (2008).

Figure 6.18 Waterbags a. Waterbag in towage b. Waterbag Pick up on to Storage Reel (credit Monohakobi Institute[31], 2008 n.p.)

c. Medusa Corporation

Medusa Corporation is based in Calgary, Alberta, Canada and produces elastic bags in vinyl, nylon, or polyester (Figure 6.19).

Figure 6.19 Medusa Bag (credit MH Waters[32], 2005 n.p.)

[31] http://www.monohakobi.com/en/research/water_bag/index.html

Medusa Corporation[33] has developed waterbags for transporting bulk water inspired by the shape of jellyfish, which remain relatively stable in storms. A small 5,000 t model was tested in the Howe Strait of British Columbia in 1997. Longitudinal encircling bands reinforced the bag (Figure 6.20).

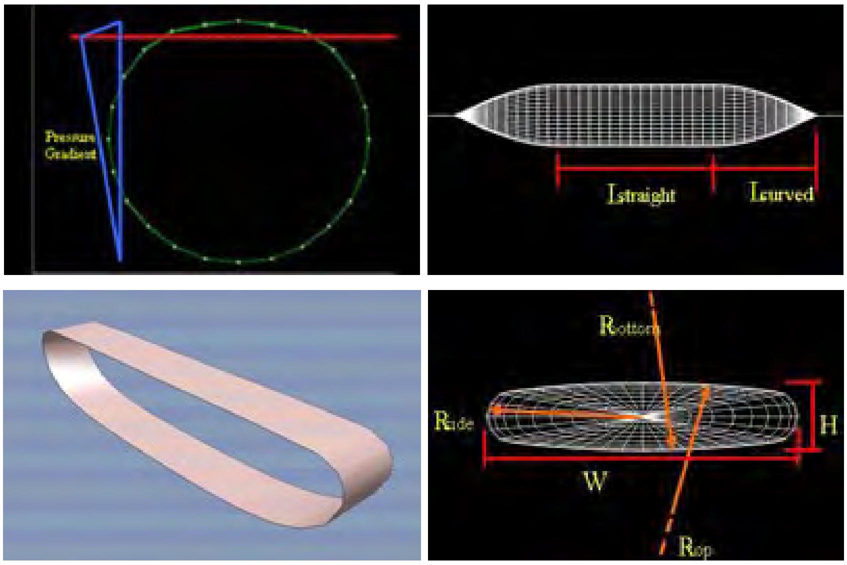

Figure 6.20 Bend for an Extremely Large Bag (three football pitches) and Optimisation of the Bag Shape (credit Shepherd [34] 2010 n.p.)

In the following years, other waterbags have been designed. During the development of these models, the bag capacity was regularly increased: from 100,000 t to 1 million t, and 1.5 million t volume bags. The company tested new types of bags, and in 2000 investigated a 4 million m^3 waterbag design. The cost of water transport in this case is estimated to be only of 1% of the cost of super tanker transport, which is about US$1 million for 4 million m^3 of water. Finally, Medusa settled on an optimal bag size given by the dimensions 650 m long, 150 m wide and 22 m wide. The bags which are the safest to operate represent a volume of 100,000 m^3 (Shepherd's projects[35]). The technology developed to produce these waterbag models is flexible, and the sizes and shapes of waterbags can be modified easily depending on the market orders and the technical requirements (the materials quality, the volume to be transported, the maritime transport requirements). These bags have a hydrodynamic profile. The difference between the density of seawater and the density of

32 http://mhwaters.com/watertransport.html
33 http://people.bath.ac.uk:/ps281/projects/waterbag old www.cix.co.uk:-savage/medusabag/index.htm
34 http://people.bath.ac.uk:/ps281/projects/waterbag
35 http://people.bath.ac.uk/ps281/projects/waterbag

freshwater allows the bags to keep equilibrium at 2.5% of their height above the sea surface, which is 60 cm above the sea surface level for pressurised bags. During transportation, tugs have to tow at low speeds, around two knots for bags to reach their mechanical equilibrium.

d. Spragg & Associates[36]

Spragg based in the US for more than 20 years invented and refined waterbag technologies, developed and tested a number of waterbags for transoceanic freshwater transportation. Some of the Spragg bags are shown in Figure 6.21 Figure 6.22 and Figure 6.23.

Figure 6.21 Filled Connected to full 'Spragg Bag' (credit Spragg[37], 2002 n.p.)

Figure 6.22 and Figure 6.23 Fabric Sleeve Connecting two Spragg Bags with Zipper during Inflation Test (credit Spragg[38], 2002 n.p.)

[36] www.waterbag.com
[37] www.waterbag.com/images/photo3.jpg

The first experiments conducted by Spragg took place in Los Angeles in 1991 with a 2,916 m^3 waterbag. Maritime engineers and textile researchers from the Massachusetts Institute of Technology (MIT) collaborated with Spragg to test appropriated materials for freshwater bags. The Spragg team developed a special system of sliding zippers for closing bags and connecting bags together, which allows bags to be added together to form 'train wagons' of 50 bags of 17,000 m^3 each, having 6 m diameter and 160 m long[39]. A closed envelope is used for interconnecting the front and back parts of two bags. In this way, the maximum inter-connection force is increased. This original solution makes the inter-connection softer and more elastic in order to reduce the tensions induced by the differential movement of undersea currents and waves. The train can therefore be towed by a single tugboat, with the only energy to overcome water friction on the bag. For improvement of towing systems of waterbags, the company CH2M-Hill Co. Ltd.[40] financed studies on loading and offloading infrastructures needed for freshwater bag transportation: pumping stations, freshwater stocking infrastructures on land, underwater pipelines towards a loading platform in the deep sea, treatment stations, and other equipment to handle the empty bags (Spragg, 2002).

e. Australian Companies: Fabric Solution Australia and Solartran

The development of Fabric Solution Australia Ltd., products could provide solutions for the transportation of freshwater in Australia. Fabric Solution Australia Ltd., develops tanks, pillows, water storage devices and flexible tanks, used in different commercial and private contexts. According to Solartran website, their "products are suitable for a wide range of applications including mining, agriculture, emergency aid, aquaculture, petroleum and oil, commercial and general industrial" (Figure 6.24[41]).

[38] www.waterbag.com
[39] http://www.waterbag.com/media/coverag.html
[40] http://www.ch2m.com/corporate/
[41] www.fabricsolutions.com.au/

Figure 6.24 a. Pillow b. Flexi Tank, Products for Freshwater Transportation (credit Fabric Solution Australia Ltd.[42], n.p.)

An Australian project for freshwater transportation by transporting water in bags, had been proposed by Edmonds, from the Burdekin River in north of Queensland to Murray River basin, to supplement supplies in the Murray River[43]. Edmonds (2006) designed a project to supply Australian cities with northern river water using the East Australian Current, which flows from the Coral Sea down the east coast of Australia to Sydney (Figure 6.25). In this project, the north of Queensland Tully River's yearly discharge of water, 3 billion t, would be captured and used to Northern River water for Australian cities (Edmonds, 2006[44]).

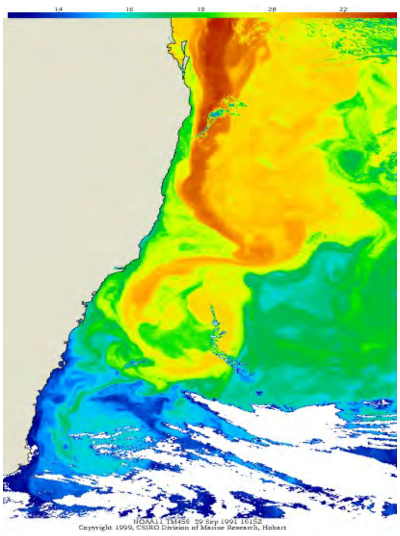

Figure 6.25 East Australian Current Flowing Thermal Image Past Gold Coast (credit Edmonds[45], 2007 Figure 2 n.p.). The colours show thermal gradients.

42 www.fabricsolution.com.au/
43 www.waterengineeringaustralia.com.au/pdf/wea_0809.pdf
44 http://www.solartran.com.au/tullywater.htm
45 http://www.solartran.com.au/tullywater.htm

To transport 240,000 t/day of water 1,600 km from the Tully River to Brisbane about 40 60,000 t containers would need to be floated on the East Australian Current. Each container would be separated from others by a distance of about 40 km (Figure 6.26).

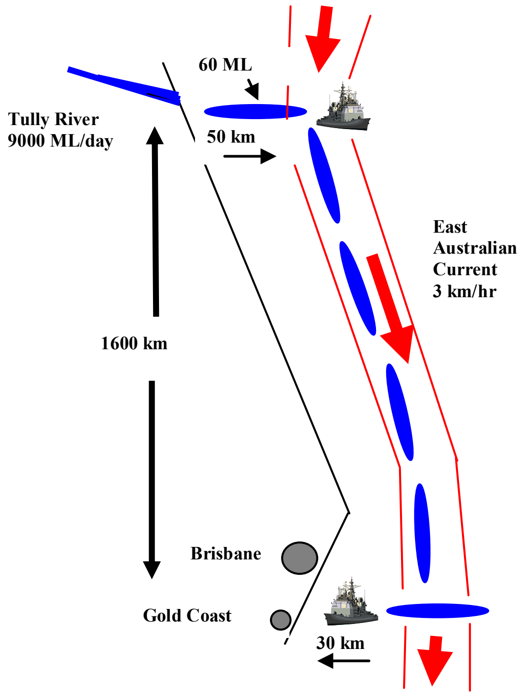

Figure 6.26 Containers 60,000 t towed into and out of the Current towards the Gold Coast on the Current Scale 1:1,500 (credit Edmonds[46], 2007 Figure 3 n.p.)

Edmonds (2007) proposed to use a bag in reinforced plastic membrane fabric of 200 m long, 30 m wide, 10 m deep (60,000 t), and 1 mm thick named 'pillow tank' containers. According to Edmonds (2007), these containers are:

> [D]esigned to be self-supporting on land and withstand considerable hydraulic pressure [when at sea]. The mass of the container is only about 20 t. Thus, after being pumped empty at the Gold Coast, the containers can be removed from the water by rolling onto a frame then loaded by a gantry onto a barge for transport back to the Tully River for refilling (Figure 6.27).

[46] http://www.solartran.com.au/tullywater.htm

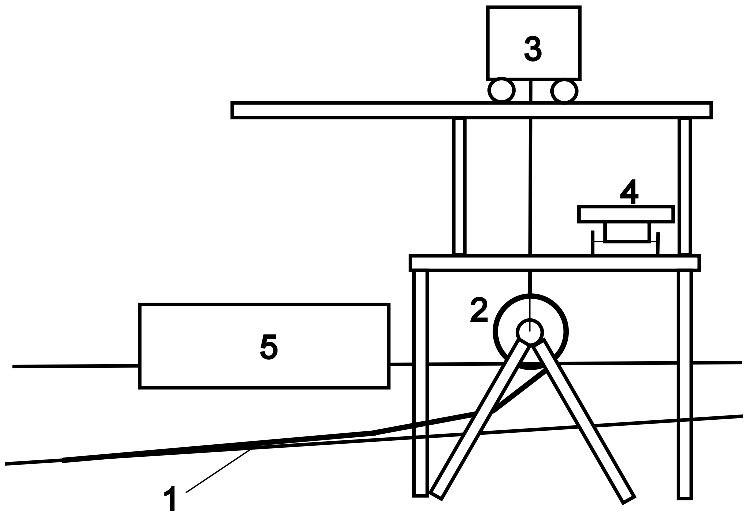

Figure 6.27 Device for Manipulation of Bags. Legend: Empty containers 1 rolled onto former 2 loaded by gantry 3 wagon 4 barge 5 (credit Edmonds[47], 2007 Figure 4 n.p.)

The 40 containers would be 97% submerged in the sea and spaced at 40 km intervals up the Queensland coast. The bags would have to be equipped with lights and radio receptors in order for other ship to be able to spot them and monitor their location.

6.4.2 Waterbags Transportation Technologies

Table 6.4 summarises the characteristics of bags produced by different companies.

Table 6.4 Some Characteristics of Bags Produced by Different Companies

Company	**Capacity (10^3 t)**	**Modularity**	**Costs Million US$**	**Characteristics**
Nordic Water Supply	35-100	1bag	20	Seatbelts, radar, harnessing
Medusa	100	1 bag	20	Environmentally friendly hydrodynamic
Spragg	200	100 bags in train	50	Zip system, offshore loading facilities
Fabrics Australian Ltd Solartran	100	50 bags in train	30	bag design, train project

We have seen that the existing waterbag technologies have been demonstrated to efficiently transport large quantities of freshwater over long distances (2,300 km) (Edmonds, 2009 p. 18). Waterbags can offer profitable and environmentally friendly water transportation

[47] http://www.solartran.com.au/tullywater.htm

systems. Furthermore, waterbags are inexpensive and environmental friendly. Edmonds (2009 p. 20) noted:

> Spilling cargo from vessels at sea is a major concern. However, spilling 250,000 t of freshwater into the sea from waterbags would have the same effect as a heavy shower of rain at sea, no effect. Colisions with a large vessel such as an oil tankers would simply part the bag and would probably be imperceptible to crew on the vessel;

The materials from which the waterbags are made can be partly or completely recycled. Recycled plastics are available in large quantities: 10 million t were recycled in 2007, representing less than 10% of the world's annual consumption (Subramanian, 2000). Australia produces more than 1.3 million t/year of plastic.

The specific infrastructures required for systems that use waterbags to transport freshwater would also be cheap, compared for example to a channel, a dam, a pipeline or a desalination plant. For the same capacity, the costs are between 10 and 100 times higher (Edmonds, 2009). Specific techniques exist to organise a liquid carriage in containers or bags. The loading and the discharging of the transported waterbags are prepared under specific conditions (criteria of stability, optimal offloading, stability forces acting on the bag, techniques for fixing the bags during transportation). Having in mind the objective of my thesis, the waterbag transportation systems presented before could be used for the transportation of melted freshwater produced by icebergs. They woud have to be adpated to oceanic conditions of the Southern Ocean and to the propulsion systems.

However, another aspect is related to the wrapping of the icebergs with a giant bag. Taking into acount the necessity to transport simulteniously melted water and ice, it would be necessary to develop and design appropriated waterbags, which are different from those existing on the market today. For icebergs giant bags must be conceived, using appropriate materials for low temperatures (-10°C). Another aspect is related to the resistence to friction and shocks, between the external part of the bag skin and the sea, and, on the other hand among the internal part of the bag skin produced by the blocks of ice floating in melted water inside the bag . Findings of studies from Sobinger, Mougin and Fuerle could be combined with the latest findings of waterbag technologies to develop a specific type of iceberg bag.

6.4.3 Ocean Currents for Waterbags Transportation

Natural marine currents could be used for icebergs transportation. Having in mind the objective of my thesis, the icebergs and the freshwater encapsulated in waterbags would drift into the most favourable maritime currents from the AAT to WA. In Antarctica icebergs drift in currents at an average speed of one to three knots.

One of the major technical challenges in icebergs transportation is how to direct an iceberg to its final destination. International Water Harvesting Group (IWHG) developed a theory of kinematics of icebergs drift, based on Epstein's (1921) theory on the drift of Continental Plates. With modern informatics tools, new software devoted to optimising the use of currents for icebergs and waterbag transportation has been developed (Bauer, 2005). According to Smakhtin *et al.* (2001 p. 17):

> The IWHG has developed software that optimises the routing for individual icebergs and includes rough melting kinetics. ... The software allows each possible iceberg route to be simulated subject to the following constraints: minimisation of energy input for tugs, minimisation of travelling time.

A safe sailing road can be defined as a function of multiple meteorological data (Kuznetsov and Rodrigue, 2009). The parameters to be taken into consideration are: natural marine currents, ice, the monsoon season, bathymetry, and the Earth's rotation parameters (Coriolis force). For the iceberg and the iceberg water transportations, special waterbag have yet to be designed with specific shapes to optimise the use of the current drifting. According to Linzee (1998 n.p.) currents: "are important to marine life as they help to move food and nutrients, making them available for photosynthesis, metabolic requirements and/or consumption". The environmental and ecological impacts of a project dedicated to iceberg transportation based on the use of currents should be monitored to ensure legal aspects at national and international levels.

6.5 Kite-Assisted New Maritime Transportation Technology

In this sectionsection I give information about a new regenerative propulsion system of kite assisted maritime transportation technology, which, in my project, could be used for icebergs and waterbags convoys for icebergs freshwater transportation. The kite assisted transport technology optimises vessel propulsion using wind force and takes advantage of strong winds above heights of masted sails (more than 150 m). The kite assisted maritime transportation technology manages wind direction and speed to achieve an optimal propulsion power, realising an important decreasing in transportation energy cost.

Two companies, Kiteship, based in the US, and Skysails, in Germany, have developed kite-assisted wind propulsion systems for sporting yachts, fishing ships and cargo vessels. In 2006 a Skysails kite system was installed on the 140 m heavy cargo freighter *MS Beluga Skysails* (132 m length, 15.8 m beam, 7.73 m draft, speed 15.5 knots). Kiteship designed and built up to 5,000 m^2 high-performance giant kites made of synthetic materials (Skyship 2006). Figure 6.28 shows a kite used for the propulsion of a commercial cargo vessel.

Figure 6.28 Giant Kite for Commercial Cargo Project (a- project and b- real image) Scale 1:50,000 Real cargo (credit Skysails GmbH&Co.KG[48], 2010 n.p.)

48 http://www.skysails.info/english/products/skysails-for-cargo-ships/
http://sciencepal.blogspot.com/2008_10_13_archive.html,
http://www.ibiblio.org/hyperwar/NHC/CRS/propulsion.htm

According to Skysails, the components of the kite assisted maritime transportation system are: the towing kite, the towing rope, the winch, the control system, the launch recovery system, the control pod and the kite mast (Figure 6.29).

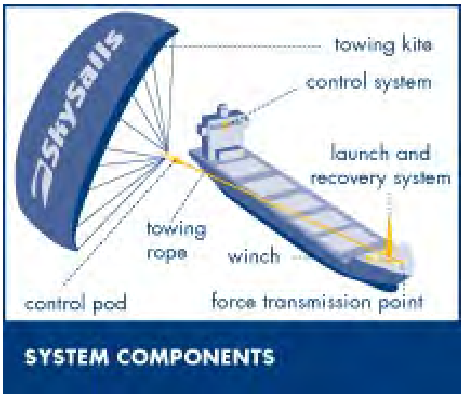

Figure 6.29 Kite Assisted Maritime Transportation System (credit Skysails GmbH&Co.K [49], 2010 n.p.)

I will discuss the following points related to the kite assisted new technology: kite installation (the structure of the system, the function of kites, the launching of kites), the navigation with kites and the safety requirements for the crew and the maintenance.

6.5.1 Kite Installation

The Skysails system is installed with a specific process (Figure 6.30 and Figure 6.31).

Figure 6.30 Module for Mast and Kite Installation (credit Skysails GmbH&Co.KG [50], 2009 n.p.)

[49] http://www.skysails.info/english/products/the-skysails-technology/

Figure 6.31 Installation of the Skysails Arrangement Module on the ROS-171 *Maarrje Theodora*, (credit Brabeck, 2010 p. 7)

According to Skysails, the installation concerns:

- the mounts;
- a control system with electronics and hydraulic connections on the foredeck comprising a small power supply and an interface to a computer supplying the system for a telescopic device;

[50] http://www.skysails.info/english/products/installation-commissioning/

- a winch and a launch and recovery system;
- a fully automatic towing kite propulsion;
- a meteorological sensor system comprising a GPS, a wind direction gauge, an anemometer and a wind optimised control routing system for automatic operation and a wind optimisation system (Figure 6. 32 to Figure 6.34).

Figure 6.32 Routing System, Radar Scanner Unit and Position of Radar Antenna on Board *MV Beluga Skysails* Earthing Sealing of the X-band (credit Wiintecc Layman's Report, 2006 p. 10)

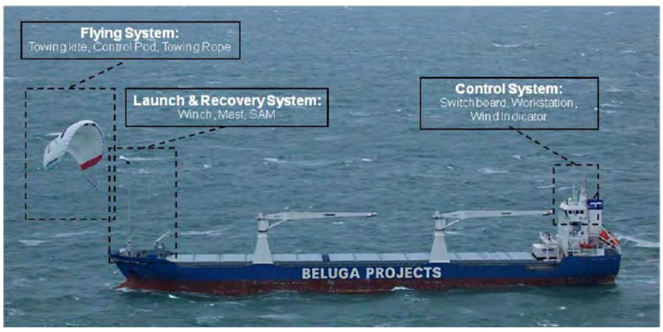

Figure 6.33 Main Components of the Skysails System (credit Wiintecc Layman's Report, 2006 p. 6)

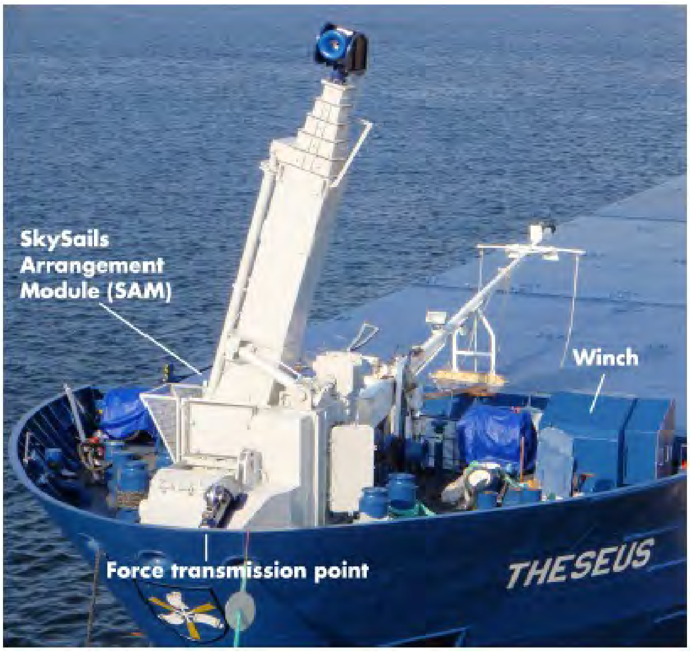

Figure 6.34 Skysails System Components on the Foredeck (credit Brabeck, 2010 p. 4)

It follows the guidelines of the NMEA - National Marine Electronic Association standard (The Georgia Engineer, 2007; Naval Architect, 2004; 2005; 2007a; 2007b). As described in the Skysails technical note (Skysails, 2009): “[T]he Skysails kite system consists of a giant kite with a big parafoil (600 m^2) connected to the ship via a towing rope. The giant Kite is assisted by a fully automatic control pod”. (Figure 6.35, Figure 6.36)

Figure 6.35 Skysails System Control Pod (credit Brabeck, 2010 p. 3)

Figure 6.36 Towing Kite Mast 3 m, Kite String 30 m kite 5 m Scale 1:100 (credit Skysails GmbH&Co.KG [51] n.p.)

According to Kiteship, their kites are composed of different composite materials: Fibreglass rods or tubing materials such as filament-wound epoxy, all-carbon graphite, aluminium carbon, and wrapped graphite. Sails can be made from lightweighted materials: Mylar, Tyvek, ripstop nylon, or other laminates. According to Skysails, the four flying lines of their kite are in "spectra fibres, which is a low-stretch synthetic yarnwith great tensile strength". (Figure 6.37 a and b).

a b

Figure 6.37Towing Rope a. Kite with Control Pod b. Towing Rope (credit Skysails GmbH&Co.KG[52], 2010 n.p., p.2)

[51] http://www.skysails.info/english/products/the-skysails-technology/system-components/launch-and-recovery-system/
[52] http://www.skysails.info/english/products/the-skysails-technology/

The launch procedure is carried out automatically in 10 to 20 mn (Figure 6.38 to Figure 41).

Figure 6.38 Skysails Arrangement Module on Forecaslte deck (credit Layman's Report, 2006 p. 9)

Figure 6.39 Skysails System Launch of the Towing Kite (credit Brabeck, 2007 p. 2)

Figure 6.40 Launch of the Towing Kite (credit Wiintecc Layman's Report, 2006 p. 9)

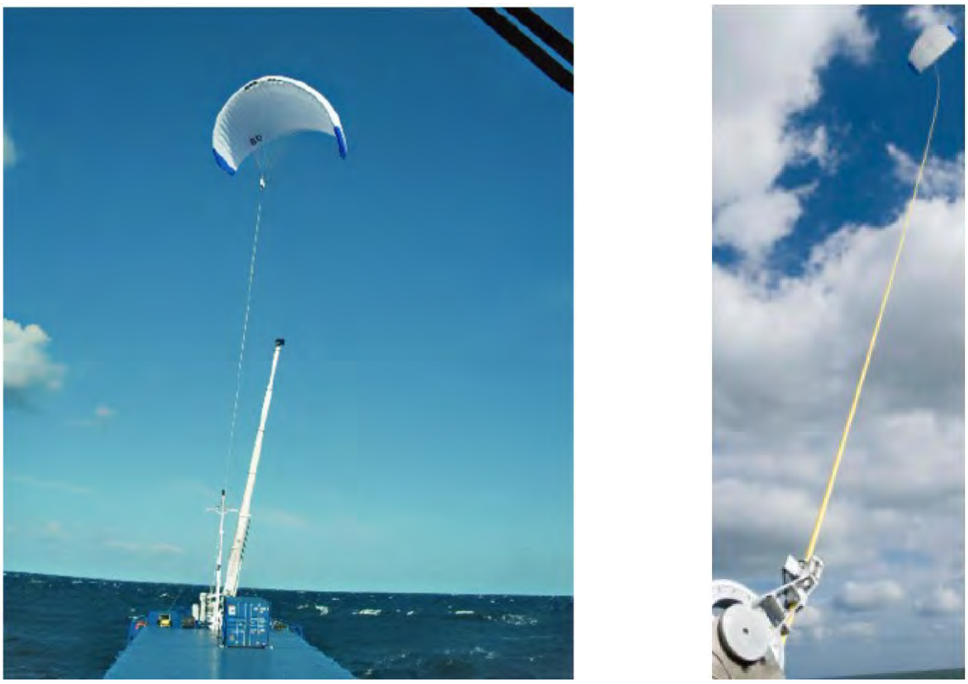

Figure 6.41 Skysails System Skysails Launching of the Skysails System aboard the *MV Theseus* (credit Brabeck, 2010 p. 6, Brabeck, 2007 p. 6)

6.5.2 Kite Operation

To launch the kite, a specific autopilot system manages the deployment and lowering of the kite (Brabeck, 2010). The propulsion operates fully automatically. According to Skysails, the launching process is based on: “[A] telescopic mast raises the towing kite which is folded like an accordion from the kite storage”. According to Skysails the Skysails kites can operate at altitudes between 100 and 500 m and the Skysails system can be used for navigation under the following conditions:

- wind forces 3 to 8 Beaufort;
- under 3 Beaufort cannot be launched but can be recovered;
- faster than 10 Beaufort the system must be recovered;
- out of dense ship traffic, 3 miles separation area.

Optimal operation zone is between 100 and 300 m as winds are more stable and stronger (Figure 6.42).

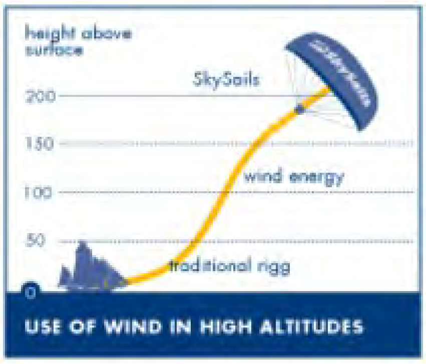

Figure 6.42 Altitude of Skysails above Sea Level (credit Skysails GmbH&Co.KG [53], 2010 n.p.)

According to Skysails: "at an altitude of 150 m, the average wind speed is around 25% higher than at an altitude of 10 m". According to Skysails "the cross-sectional profile of the kite is adjustable to achieve optimal aerodynamic properties under various wind speed and weather conditions". Therefore, Skysails claims that their kite-assisted propulsion systems can have a propulsion power of up to 5,000 kW. Towing power is a function of the drag coefficient, the cross sectional area of the transporting device and the speed of towing (Skysails, 2006a p. 14).

6.5.3 Navigation

According to Skysails the kites also are operated automatically:

> The autopilot installed on the bridges uses two computers for controlling the kite, one supervises the kite to flight in eight in the sky and the second one adjusts the kite direction from the pod ... data are transmitted by means of a cable integrated into the towing rope. (Figure 6.43)

Figure 6.43 Figures of Eight in the Sky (credit Skysails[54], p.10)

[53] http://www.skysails.info/english/products/the-skysails-technology

By doing figures of eight the kite power is optimised. Simulated shapes of the kite during surfing are shown in Figure 6.44.

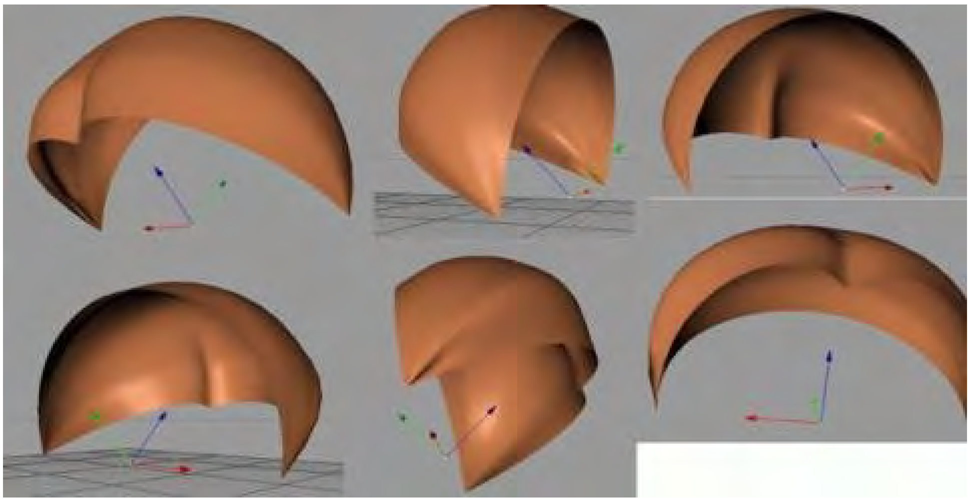

Figure 6.44 Simulated Shapes of Kites During Kitesurfing Out Leader™ Kite Study (credit Kiteship[55], n.p.)

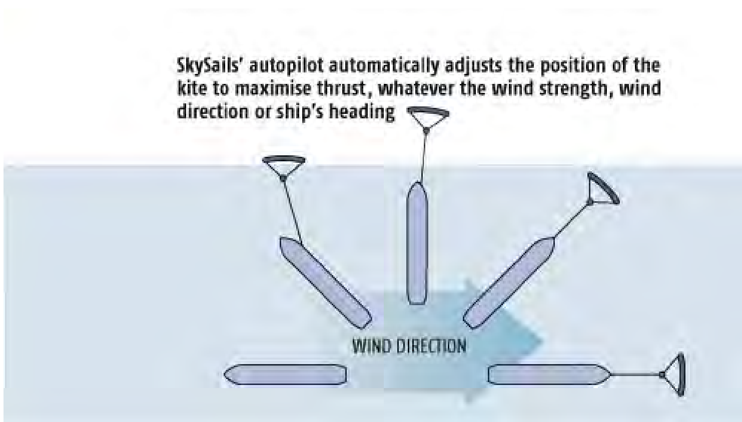

Figure 6.45 Simulated Shapes of Kites During Kitesurfing (credit Skysails, n.p.)

For navigation, the control system manages the kite flight and the sailing (Figure 6.46).

[54] http://www.skysails.info/english/products/the-skysails-technology/advantages-in-detail see also http://www.skysails.info/english/information-center/news/news/article/hubschrauber-meldet-skysails-in-der-nordsee/506/cc972236e7/
[55] http://www.kiteship.com/photoview.php?show=outleaderstudy.jpg

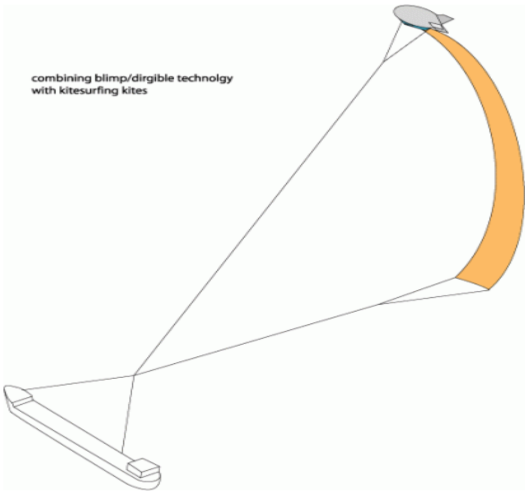

Figure 6.46 Kite Propulsion Combining Blimp/Dirigible Technology (credit Kiteship[56], 2010 n.p.)

The steering system of the Skysails system is composed of the control pod, which is used to direct the kite and the control system, which is used to direct the vessel. According to Skysails one of the main technological advantages achieved with kite assisted propulsion system is the fact that the towing kite can be navigated dynamically (Figure 6.47).

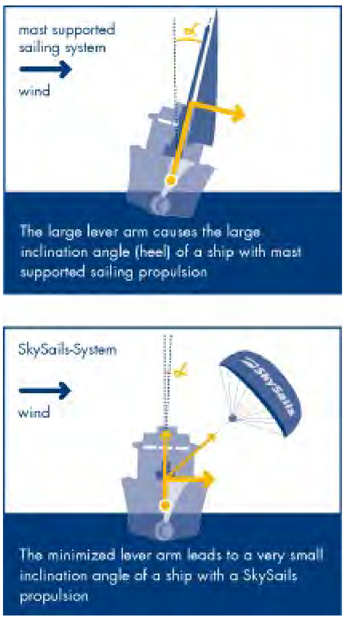

Figure 6.47 Heel Reduction Produced by the Kite with Skysails System (credit Skysails GmbH&Co.KG [57], 2006b p.11)

[56] http://www.kiteship.com/photoview.php?show=kitestudy3.gif
[57] http://www.skysails.info/fileadmin/user_upload/documents/Dokumente/SKS_Broschueren/EN/EN_Technology_Information.pdf

The dynamic navigation decreases the heel, the inclination angle of the ship and the water friction on the vessel. The kite tractive force can be optimised. According to Brabeck (2010 p. 3): “the recovery process is performed in the reverse order of the launch. The entire recovery procedure is carried out automatically in 10 to 20 mn”.

6.5.4 Safety, Crew and Maintenance

The safety of the system is ensured through an integrated dynamic power, which allows the kite flying and navigation control such as:

- the horizontal position of the towing kite can be varied;
- the dynamic winch control releases and retracts the towing rope as needed;
- the autopilot can adjust the towing kite to a ‘neutral zenith position’, in 30 s;
- the launching or the recovery is in about 20 mn;
- the same kite is used for all wind intensities;
- the system is safe when the weather conditions cannot be forecast precisely enough;
- reinforcement of the vessel foredeck may be required for stability.

The kite-assisted navigation system is complex therefore the crew has to be trained for the handling of control systems related to the stability and manoeuvring performances. The maintenance can be serviced offshore (Skysails, 2006a).

6.5.5 Discussion

for the steering of the waterbags convoy of transporting melted iceberg freshwater of my icebergs transportation project, the kite-assisted connected waterbags would be equipped with a control system for navigation via satellite. The following points must be developed:

- the kite functioning would be automated and could provide a reliable direction control for waterbag train sailing and steering;
- the kite structures as well as the waterbag structures need to be correspondingly dimensioned so that the stability of the convoy could be assumed;
- a steering device similar to the US Patent 6910434 one can be used for the waterbag train;
- a minimal crew would be necessary to operate a transportation system that used kites as a propulsive force for the movement of icebergs.

6.6 Optimisation of Icebergs Transportation with new Technologies

A number of factors including the variable costs of transportation, the distances to be travelled, the service patterns of transportation, and transportation’s capacity utilisation determines maritime routing (Kuznetsov and Rodrigue, 2009). Other factors that influence the efficiency of transportation include fluctuations in energy prices and the cost of labour, changes to the financial policies of nation-states, and the new technological processes. In terms of different transportation options, Kuznetsov and Rodrigue (2009) argued that over medium and long distances ocean ship transportation becomes the most cost effective. In this case, the propensity to use larger transportation systems triggers a rationalisation in the routes selected. The development of iceberg transportation is linked with technological, economics and infrastructural processes structured along local and regional regulating points. In the case of iceberg transportation system from Antarctica to WA, the transportation capacity depends on the energy costs and the operational costs. The operational costs are preset, but the energy costs can be minimised by the use of natural energies (Tietenberg and Lewis, 2009). The use of these energetic resources determines the pattern of new routes (Sørensen, 2007). Hence, for the iceberg transportation systems, the use of these energetic resources is optimal if the transportation route follows the pattern of the winds and the currents, which from Antarctica to WA are favourable. The possible exploitation of these favourable currents and winds is an important advantage for the development of an iceberg transportation system. They define a corridor of transportation from the AAT to WA (Figure 6.48). In this Skysails map, it appears that the currents from the AAT to WA are favourable.

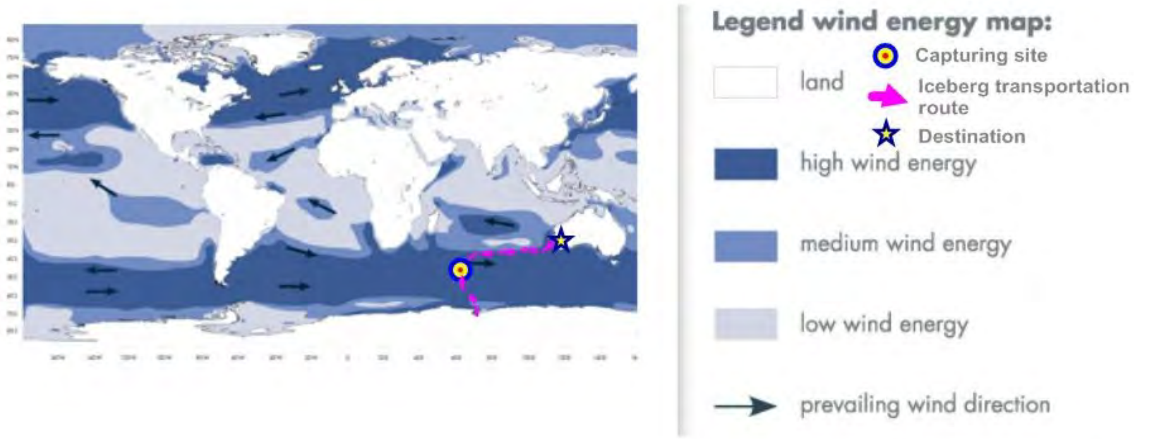

Figure 6.48 Ocean Currents strength (from Skysails, 2007 p.9[58])

[58]http://www.skysails.info/fileadmin/user_upload/documents/Dokumente/SKS_Broschueren/EN/EN_Technology_Information.pdf

Georges Mougin conducted in 2010 a simulation with the company 3Ds to evaulate the feasibility of an iceberg towing transportation from Newfoundland to the Canary islands in Spain. The simulation concludes that a 130 t traction tug boat could tow successfully a 7 million t tabular iceberg in about five months, the iceberg losing on average 38% of its mass (Figure 6.49).

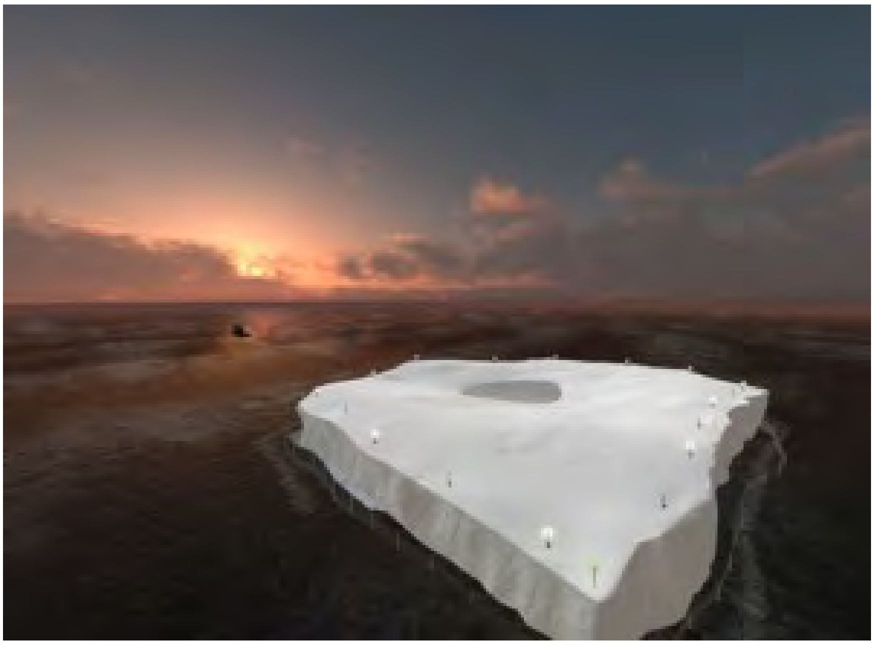

Figure 6.49 Iceberg Transportation Simulation (credit 3DS, 2010[59])

We saw what was able to be done in regards to iceberg transportation specific needs concerning iceberg selection, iceberg harnessing, iceberg water transportation and propulsion and sailing technologies using renewable energies. In these areas, innovative breakthroughs have been made recently (waterbags and kites) which have resulted in the possibility of reconsidering the feasibility of an iceberg transportation project, compared with previous projects discussed in Chapter 5. Assuming that the innovation presented in this chapter could be adapted to an iceberg water transportation system, some specific areas remain to be further investigated:

- the stability and structures providing reinforcements during the iceberg melting processes;
- the separation of iceberg from the melted freshwater, during transportation and

[59] http://perspectives.3ds.com/environment/how-to-tow-an-iceberg-pt-1/

- the improvement of the propulsion system with kites, winds and steering with ocean currents to supplement the costs of fossil fuel for icebergs transportation.

The model of iceberg transportation technical system, which will be designed based on this analysis will be exposed in the next chapter and is an original contribution of this thesis.

6.7 Summary

This chapter has set out to introduce some of the technologies that could have potential application for towing icebergs from the AAT to WA and transporting the resulting melted freshwater. The first part of the chapter discussed the geographical situation of the resources (icebergs), the climatic conditions, icebergs detection selection and corresponding remote sensing operations. It appears that large icebergs can be selected according to their location and physical characteristics. It is also possible to manoeuvre icebergs with specific navigation operating techniques. Icebergs harnessing and risks associated to this operation are discussed. Considering the difficulties related to iceberg transportation one option would be to melt the iceberg and to transport the icebergs melted water with a convoy of waterbags. Waterbag technology developed by several specialised companies has been commented. Waterbags have important potential application in water transportation and iceberg transportation. The iceberg operating system could use a specific giant bag having similar characteristics of to those of melted freshwater bags. It was suggested to use natural regenerative propulsion systems, environmental sound sources, the winds and the ocean currents to steer and transport the convoys of waterbags. New kite assisted maritime transportation technologies are discussed and suggested for icebergs transportation as well as for waterbags convoys transportation, having in mind that the kites can develop enough power to steer and to provide direction and speed to an iceberg or melted waterbags convoys. Therefore, a model of iceberg transportation based on the suggested technological solutions will be proposed in the next chapter.

Chapter 7 Designing a New Iceberg Transportation System

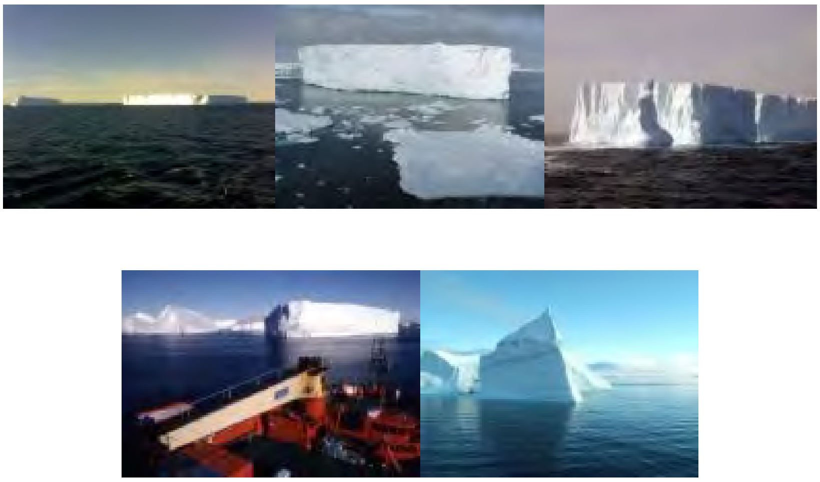

Figure 7.0a Iceberg (NOAA, n.d n.p.[1])

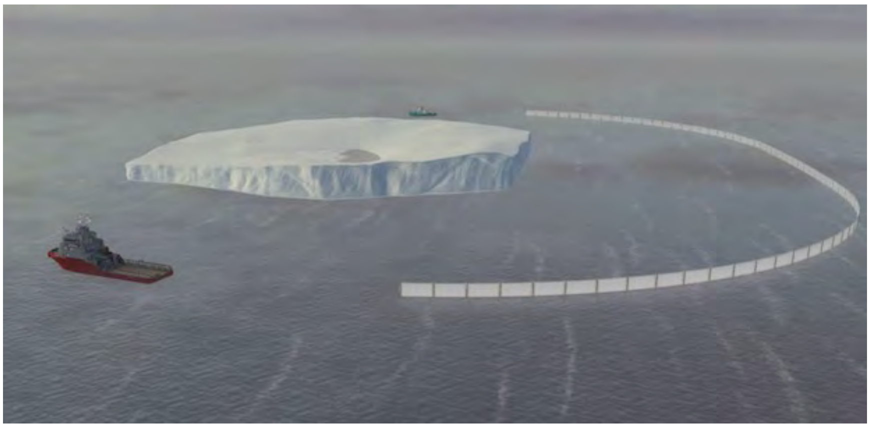

Figure 7.0b Iceberg Transportation simulation (credit 3DS, 2010[2])

Progress consists in increasing the benefits of [men's] efforts by
the [progressive] way they are combined.
(Translated from Weil, 1935 p. 28)

[1] http://oceanexplorer.noaa.gov
[2] http://perspectives.3ds.com/environment/how-to-tow-an-iceberg-pt-1/

Chapter 7 Designing a New Iceberg Transportation System

In Chapter 5 the main factors identified as critical for icebergs transportation from the AAT to WA were:

1. ensuring iceberg stability during transportation;
2. avoiding mass loss of iceberg water;
3. avoiding the high cost of fossil fuel for the transportation systems;
4. recognising sustainability issues and employing environmentally friendly materials and technologies.

While some technologies that could be used to address these issues have already been discussed (Chapters 5 and 6), in this chapter an original transportation process for the operating of icebergs water from the AAT to WA is advanced. This chapter will focus on the technical feasibility of ensuring iceberg stability during transportation and avoiding the high cost of fossil fuel for the transportation systems.

My original contribution to this subject, and the core of this thesis, is to 'split' the challenge of transporting melted freshwater from icebergs from the AAT to WA into two distinct processes. The first process involves the collection of the water from the melting iceberg enclosed in a megabag into an attached temporary collar base. It is a transferring operation. The second process involves transporting the collected melt freshwater in numerous waterbags from the collar to the selected destination.

The proposed new system includes:

- a specific process to capture and wrap the iceberg in a 'megabag';
- an attached collar collection system offshore temporary base and a net that can recover iceberg melted freshwater and stabilise the iceberg during melting;
- a new type of waterbag for oceanic freshwater collection and transportation, assembled in a train that is propelled by kites and maritime currents.

The main logistical aspects include:

- icebergs selection (detection and environmental assessment);

- pre-package operations (iceberg capture, harnessing);
- iceberg wrapping (in a megabag, with an attached temporary offshore collar installation, a connection system to the megabag, and a netting system);
- iceberg freshwater processing (in a megabag and transfer to a collecting collar);
- iceberg freshwater loading (from the collar to freshwater bags);
- freshwater bags transportation (waterbags assembly in a train that is towed and launched into a maritime current, with propulsion assisted by wind energy kites, all under continuous satellite surveillance);
- trajectory and route optimisation;
- freshwater delivery to the expected destination and tests for water quality and sanitary control of bags;
- cleaning and maintenance of the freshwater bags for the next transportation cycle or for other purposes;
- cleaning and maintenance of the megabag, collar, net and other tools used during transportation cycle.

The elements of the system of transportation are illustrated with graphic simulations with conceptual sketching and basic modelling tools. According to Hult and Ostrander, (1973[3]) designing models is a valuable attempt to visualise a global method for iceberg water transportation. These models were designed with the objective to provide a basis for further technical experiments.

7.1 Iceberg Detection, Selection and Environmental Assessment

Large tabular iceberg selection for freshwater transportation would require consideration of factors including environmental characteristics (currents and winds, meteorological data, the pressure lines, isolines predicting, fog probability, and storms), accessibility (location and operating site), iceberg size (volume of water and harnessing) and iceberg stability during transportation (iceberg shape having no cracks or fracture lines). Environmental data collection would have to meet all legal requirements, as discussed in Chapters 8 and 9.The objective of this chapter is to demonstrate whether, if an iceberg originates from the Amery Ice Shelf at a latitude of 66° S and drifts 1,500 km eastward until it reaches 55° S, it would be technically feasible to direct it another 600 km to warmer waters east of the Kerguelen Islands, at around 48° S, where its melting rate would increase.

[3] http://www.rand.org/pubs/reports/2008/R1255.pdf

The studies of Hult and Ostrander (1973) constitute a valuable reference for iceberg transportation projects from Antarctica. Hult and Ostrander estimated that iceberg acquisition from the Ross Ice Shelf would be ideal for a project of transportation through the Pacific Ocean to the US and Japan whereas east Antarctica icebergs acquisition would be more suitable for the rest of the world. The acquisition method of the project presented in this chapter differs with the propositions of Hult and Ostrander. In a pragmatic attempt to consider iceberg selection process, the location of acquisition would be defined in relation to the location of delivery in order to minimise transportation distances. Icebergs in the acquisition zones would have different original locations, however icebergs coming from the closest locations of origin would be preferable because of the integrity and the robustness of their structure. Hult and Ostrander (1978) reported that acquisition locations could be selected between 65° S, and 60° S whereas for the same reasons as explained previously (and for environmental considerations stated in Chapter 8), the acquisition location of a project based on the maximisation of the use of the currents to transport icebergs from the AAT to WA would be around 55° S for an initial project. At a later stage and a larger scale, icebergs could be acquired a bit further south depending on the concentration of tabular icebergs which varies annually.

Icebergs drifting in the acquisition location region are driven by Sub Antarctic currents and winds and generally reach an average speed of 3.5 km/h (Smith *et al.*, 2001). In this project the maritime currents would propel the iceberg while wind energy and kites would secure drift direction.

The Weddell Sea region would also be a viable option as it has a satisfactory concentration of large tabular iceberg with an absence of cracks, fracture lines and other defects as identified in Chapter 3, ideal currents for freshwater transportation to WA as assessed in Chapter 3 and optimal characteristics in terms of environmental safety as identified in Chapter 4 (Hamley and Budd, 1986[4]; McAyeal *et al.*, 2006[5]; Jacka and Gilles, 2007[6]; see also Appendix 3).

The detection and location of a selected iceberg is checked by satellites ship and helicopter. Impulse radar is used to determine detailed characteristics of the iceberg (Power *et al.*, 2001). According to the iceberg management procedures suggested by the International Ice

[4]http://www.igsoc.org/journal/32/111/igs_journal_vol32_issue111_pg242-251.pdf
[5]http://www.agu.org/journals/ABS/2006/2006GL027235.shtml
[6]http://www.igsoc.org/journal/53/182/j06j118.pdf

Patrol in the Grand Banks of Newfoundland, a daily survey allows reliable prediction of an iceberg's drift direction over the next days as identified in Chapter 6.

Large tabular icebergs would be chosen for the stability of their structure and for their strategic location between the Weddell Sea and the Kerguelen Islands. The size of iceberg considered appropriate for this proposal would have a volume ranging from 25 million t of up to 2 billion t. Icebergs with a ratio of length to width of 5 and a ratio of width to thickness of 5 should be chosen to minimise risks against breakup and maintain stability and integrity (Spandonide, 2004). Preliminary estimates of Hult and Ostrander (1973) indicated that 100 m thickness iceberg would be strong enough against the stresses from the largest wind wave systems of the heavy seas that might be encountered. This would generate edge erosions and in case of extreme conditions (such as a tsunami), the iceberg would tend to break into lengths greater that the thickness and would stay stable in flotation. A plain elliptical above water shape of a tabular iceberg would correspond to an optimal stability of the iceberg (Jones, 2006; McClintock *et al.*, 2007). Several previous projects suggested to trim the iceberg to optimise their shape to improve their drifting abilities. According to Weeks (personal communication 2011) "chopper operation is a bit of a production but with an experienced crew, not that difficult. However it is expensive". An iceberg with a plain uniform surface allows helicopter landing, technicians transportation and equipment installation for iceberg wrapping. The vessel's detection equipment would provide vital, detailed information on the characteristics of the iceberg that are salient to transportation (sizes).

7.2 Pre-packing Operations

The equipment for iceberg capture, harnessing and wrapping procedures will be presented.

7.2.1 Equipment

A survey vessel carrying a helicopter equipped with radar meets with the iceberg. The use of a helicopter is a very complex exercise for the crew. However, it is feasible, as demonstrated in Figure 7.1 and Figure 7.2 which show a helicopter flying over an iceberg and landed on a tabular iceberg in 2006 in New Zealand.

Figure 7.1 Helicopter over Iceberg, Length 10 m, Scale 1:50,000 New Zealand (credit V Aviation[7], Helicopters Otago Ltd. 2006)

Figure 7.2 Helicopter landed on iceberg, Length 10 m, Scale 1:500, New Zealand (credit V Aviation[8], Helicopters Otago Ltd. 2006)

The workers would be entrusted with the task of installing and operating the wrapping system by attaching the wrapping equipment to the top of the iceberg through the use of a winch (Hult and Ostrander, 1973). The workers could be landed on the tabular iceberg with the same type of device by helicopter. Figure 7.3 shows workers operating a crane-type landing platform in Antarctica. Cranes of several thousand tonnes of lifting capacity could be fixed on tabular icebergs (Hult and Ostrander 1973; Page[9], 1986). In bagging systems, issues related to the changing of the shape of the iceberg because of the melt can affect

[7] http://www.newzeal.com/theme/heli/Icebergflight.htm
[8] http://www.newzeal.com/theme/heli/Icebergflight.htm
[9] http://www.freepatentsonline.com/4621946.html

closing designs. These issues were underestimated and ignored. A tightening process was not proposed by any patents. A system of rivets would therefore be needed to adjust the shape of the bags and nets to the changing shape of the melting iceberg. It would also distribute the weight lifting forces of the bags and the nets efficiently around the iceberg.

Figure 7.3 Crane-type Landing Platform, Length 7 m, Scale 1:500 (credit Rhian[10], 2005)

The scales of shipping equipment which could be used for iceberg capturing and harnessing are shown in Figures 7.4a to e. The operating vessel would transport operational materials such as the iceberg megabag, the collar bag, the nets, and tow lines, and the waterbags.

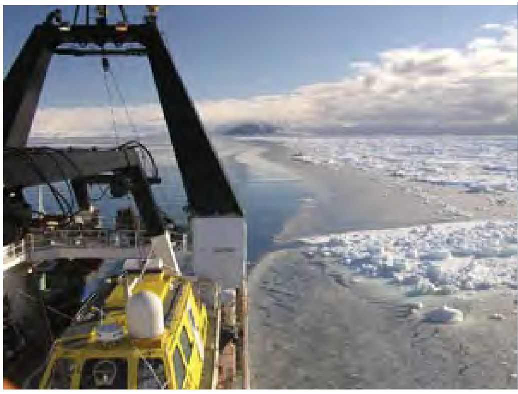

Figure 7.4a *The Tangaroa* 1:15,000 (credit Peng, 2005 n.p.)

Figure 7.4b *The Nathaniel B Palmer* Ross Sea (credit Rhian, *et al.* 2009 n.p.)

[10]http://rhiansalmon.com/2005/03/the-birth-of-icebergs/

Figure 7.4c *The Astrolabe* at bay near Dumont d'Urville (credit Dargaud, 2008 n.p.[11])

Figure 7.4d Retrieving the Tow Line, *West Navion* in Distance (credit McKenna *et al.*, 2007 p. 24[12])

Figure 7.4e Iceberg F170 Under Tow by *Havila Charisma*, *West Navion* in Background 2000 (credit McKenna *et al.*, 2007 p. 25[13])

[11]http://www.gdargaud.net/Antarctica/InfoAntarctica.html
[12]ftp://ftp2.chc.nrc.ca/CRTreports/GB_Iceberg_Manage_Overview_07.pdf
[13]ftp://ftp2.chc.nrc.ca/CRTreports/GB_Iceberg_Manage_Overview_07.pdf

7.2.2 Capture

As noted in Chapter 6, there are a number of different technologies for capturing an iceberg. The capturing process designed by the C-CORE (C-CORE, 2004a[14]) as discussed in Chapter 6, would be appropriate for the project of iceberg transportation discussed in this chapter. For iceberg manoeuvring and stabilisation after capturing, it is necessary to obtain regular iceberg geometry. However tabular icebergs have irregular edges and it creates a difficulty for iceberg harnessing (Figure 7.5).

Figure 7.5 Iceberg off Antarctica (NASA[15], 2010 n.p.)

The first step would therefore require flattening to some extent the surface of the iceberg (Hult and Ostrander,1973; Shick, 2003[16]; Abramovitch, 2004[17]). The second step would require establishing a regular geometry of the lateral sides of the iceberg, which would be achieved by wrapping the lateral sides of the iceberg into a protective sheet having several layers of cylindrical elements made of foam. The cylindrical elements around the iceberg would contribute to iceberg protection against erosion by waves. The belt of foam elements layer would allow melted water to pass through inside the megabag, while protecting the structure of the megabag walls which would be used for wrapping the iceberg. The foam layer would act to 'sculpt' the iceberg by rounding its edges. The belt would be tightened by the winch or rivet system. The cylindrical elements in longitudinal view are shown in Figure 7.6a and b.

[14]ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Oceans_Iceberg_Profiles_04.pdf
[15]http://www.adventure-journal.com/wp-content/uploads/2010/02/nasaiceberg.jpg
[16]http://www.freepatentsonline.com/6688105.html
[17]http://www.freepatentsonline.com/y2004/0265062.html

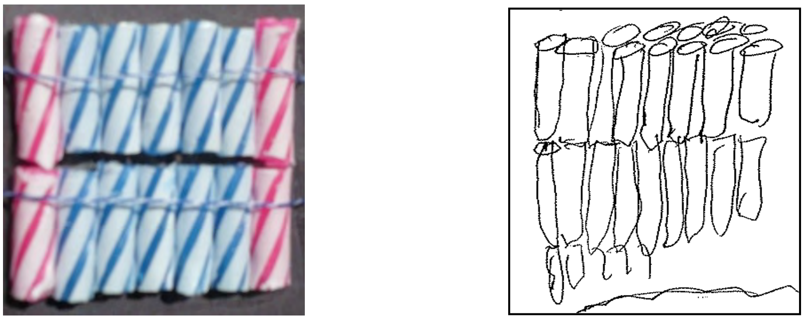

Figure 7.6a and b Cylindrical Elements of Foam for Iceberg Protection Scale 1:500

As the iceberg melts, the cylindrical elements could be kept tight around the iceberg with a first net attached to the winch located at the top of the iceberg (Figure 7.7 and Figure 7.8)

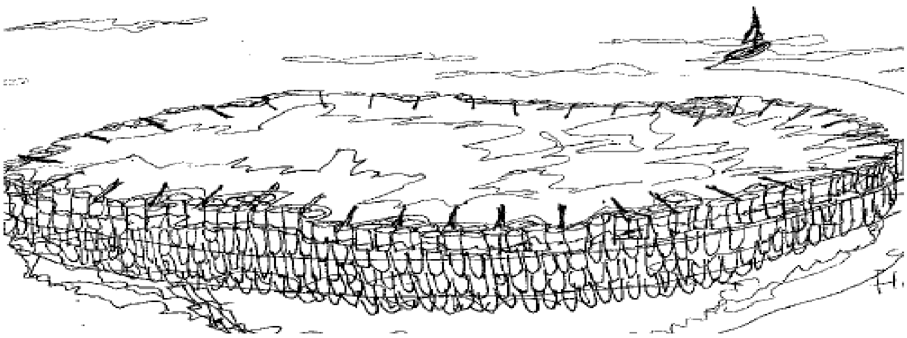

Figure 7.7 Iceberg Protection with Cylindrical Foam Elements. Iceberg Length 0.6 km, Foam Depth 300 m, Width 150 m, Scale 1:50,000

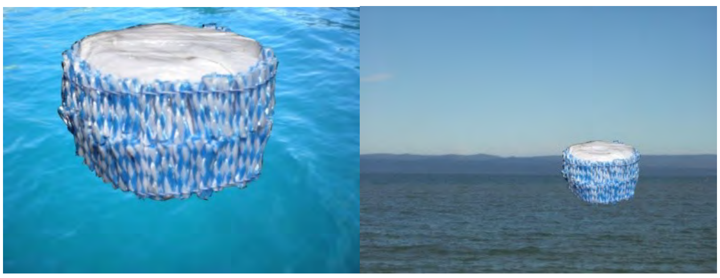

Figure 7.8a and b Iceberg Protection with Cylindrical Foam Elements. Iceberg Length 0.6 km, Foam Depth 300 m, Width 150 m, Scale 1:50,000

This would improve the stability of the iceberg as it would melt and, because of the uniform external force of the net on the iceberg, it would diminish iceberg fracturing risks. For a 25 million t iceberg, the belting process with cylindrical elements could be performed in two days, which corresponds to the same scale of wrapping studied by Hult and Ostrander (1978). The crew would be trained in wrapping, netting and collar operations. In 2010 Mougin and Mauviel proposed a new type of material. Their system is composed of floating belt 6 me above the waterline and 6 m below comprising strips of ''non-woven geotextile'' to decrease the iceberg's melting. This skirt would protect the iceberg (3DS, 2010[18]).

7.2.3 Internal Netting

An internal netting system consisting of a flexible holding and harnessing structure equipped with wire screen reinforcements designed to limit iceberg calving, splitting or breaking would be passed around the iceberg. The rivet winch would progressively tighten and compress the internal net around the iceberg, allowing the net to adjust to the changing geometry of the iceberg during melting. The netting system would enhance the stability of the iceberg and limit iceberg calving, splitting or breaking risks. The netting system would help to maintain a steady air pressure between the iceberg and the megabag in which it is wrapped and consequently reduce the variability of melting rates across the iceberg. The netting system would be installed around the iceberg by a vessel, as shown in Figure 7.9, following the technology described by Rowden-Rich (1986) for towing an iceberg or the technology recommended by Ocean Ltd (2007) for icebergs harnessing.

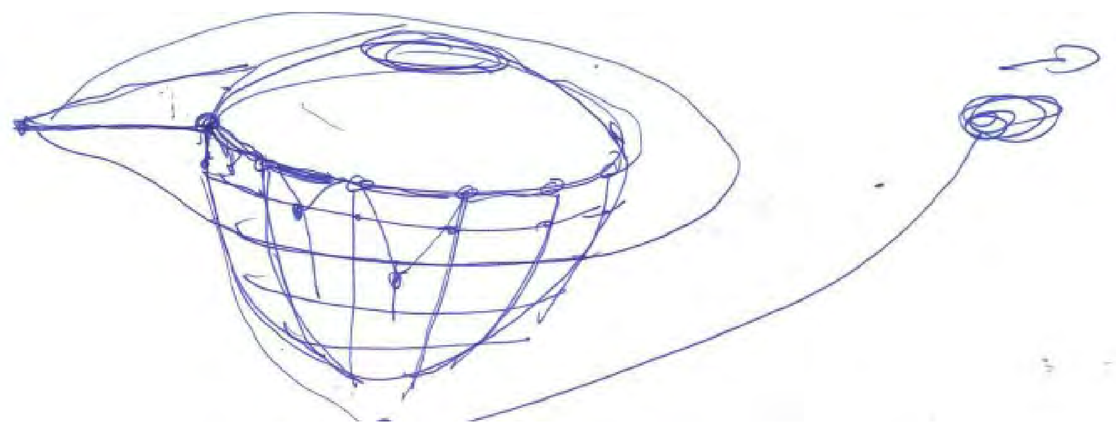

Figure 7.9 Netting an Iceberg. Scale 1:50,000 Collar 1.5km

[18] http://www.3ds.com/icedream/scientific-simulation-in-3d/pilot-project/

Net encasing systems for iceberg transportation have been studied by Merrill (1966), Sobinger (1986), Hewlings (1989[19]), Fuerle (2003[20]), Abramovitch (2004[21]), Shick (2004[22]) and Mougin and Mauviel (2011[23]).. They were studied for their stretching abilities which could enhance icebergs stability. Solutions for many applications and conditions are available. Netting systems strength depend on several parameters:

- the net shape. Round shaped nets are generally stronger; Dymaxion structures could also be considered (Buckminster-Fuller, 1960);
- reinforcements;
- the fabrication techniques. Net can be knotted or cabled with different shapes (spiral, orthogonal knots). Webbing has high breaking strength;
- the materials. Nets are traditionally designed with PVC, polyester polypropylene, high-performance polyethylene, polyamide, nylon, rope. HPPE has high resistance in terms of cyclic loads, knot fatigue, elongation changes and abrasion (Wanchana *et al.*, 2002). Some materials have high stretch capabilities before breaking and absorb shocks; it could be reinforced with light metallic structures such as aluminium;
- the diameter of the strings and the diameter and shape of the twines;
- the weight. For instance a 250 g/m^3 net for a 25 million t iceberg would have a 1000 t net.

Netting systems are able to sustain high level of pressure. The resistance of the netting system for a melting iceberg of 25 million t would depend on the net structural properties (fatigue properties, the breaking load limit, tensile and knot cycling load, maximal load at failure) and the utilisation conditions of stress (the range of axial stress and internal pressure).

For the internal net, the net would mainly support the megabag and adjust its shape to the iceberg shape as the iceberg would change during its melt and give stability to the iceberg by adjusting to its shape with the megabag. For a 25 million t iceberg, the megabag would weigh 25,000 t partly hold by the floating iceberg and its buoyancy.

The netting system would be composed of a system of connected circular rails to support the megabag and tighten it. The bag would have connectors inserted inside the rails. The netting

[19] http://www.freepatentsonline.com/4854780.html
[20] http://www.freepatentsonline.com/6616376.html
[21] http://www.freepatentsonline.com/6688105.html
[22] http://www.freepatentsonline.com/y2004/0265062.html
[23] http://www.3ds.com/icedream/scientific-simulation-in-3d/pilot-project/

system would be tightened by the rivet or winch system, lifting the bag as the iceberg would melt and its melt water would be transferred in the collar. Such a netting system could be developed and tested with further experiments concerning the specific conditions of the Southern Ocean (exposure to waves, cold, U.Vs, salt, wind).

7.2.4 Iceberg Wrapping

In Chapter 5 it was noted that iceberg transportation in a bag was estimated as technically problematic in terms of melting. To avoid this problem, the iceberg could be wrapped in a megabag. However in Chapter 5 it was noted that iceberg transportation in a bag was estimated as technically problematic in terms of stability (Hult and Ostrander, 1978; Mougin, 1981; Sobinger, 1985). Inside a megabag the melting iceberg would be continuously balancing in a variable level of melting water. To avoid this problem, the iceberg could be wrapped in a megabag in order to collect its melted water and transfer them later in a collar. The megabag would entirely cover the iceberg. The wrapping material would have to be light, waterproof and resistant at low temperatures and shocks caused by ocean waves and ice pressure. According to Hult and Ostrander (1973) a 3 m thick envelope of Mylar would provide satisfactory protection for a large tabular iceberg (> 20 billion m^3). However the envelope would lose its elasticity and the wrapping process would become very hard to complete. Therefore for a 25 million t iceberg, the wrapping envelope of the megabag could be made from a 1 m thick reinforced plastic membrane and have a dry weight of 20,000 t (Hult and Ostrander, 1973; Sobinger, 1985). Modern technological advancement for composite materials could improve the technical characteristics of the materials appropriated for this purpose. For example another option for the envelope would be to design a sheet composed of several layers of thickness of several centimetres attached to each other in order to keep the global flexibility and the flexibility of the plastic membrane. There are several methods of wrapping, depending on iceberg size and shape (elliptical or rectangular sections), such as sliding down over the sides of the iceberg or enveloping the iceberg by sliding the megabag around the iceberg. Iceberg wrapping could be performed using different techniques:

- the megabag could be passed over the sides of the iceberg:

A helicopter could transport a team of technicians onto the selected iceberg together with the equipment needed and the megabag. Then the megabag could be fitted to the iceberg by sheets, sliding down over the sides of the iceberg under their own weight. The envelope would then be sunk by weights. The wrapping envelope would slide down the iceberg sides and come back to the waterline. The wrapping could be completed with a device using hydrodynamic forces of air-inflated buoys, generated either by a remotely operated vehicle (ROV) or by a boat that would pull the sides together (Figure 7.10 and Figure 7.11).

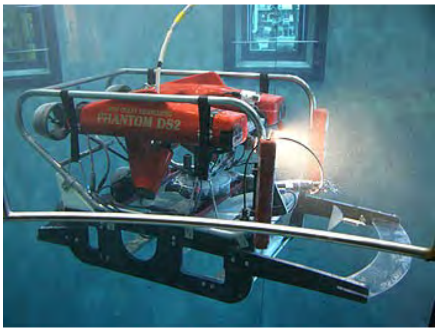

Figure 7.10 Phantom DS2 ROV 1.5 m, Scale 1:1,000 (credit Reisenbichler[24],MBARI 2008 n.p.)

Figure 7.11 Single Vessel Towing and travel pictures[25]
(credit McClintock, McKenna and Woodworth-Lynas 2007 p. 23[26])

- the envelope could also be passed around the iceberg using the internal net with a system of rails or pulleys attached to the iceberg;

Figure 7.12 shows the harnessing procedure used by a single vessel for iceberg towing, which is standard practice in iceberg management. The wrapping procedure in this project could follow exactly the same manoeuvring:

[24]http://www.mbari.org/news/homepage/2008/icebergs2.html
[25]http://www.flickr.com/photos/24012618@N03/2282698121/
http://www.flickr.com/photos/83024403@N00/3269151803
[26]ftp://ftp2.chc.nrc.ca/CRTreports/GB_Iceberg_Manage_Overview_07.pdf

- the iceberg could also be enveloped by sliding the megabag around it. A mobile megabag having a geometry similar to that of a flexible pillow membrane container attached to the foam protective sheet would be installed.

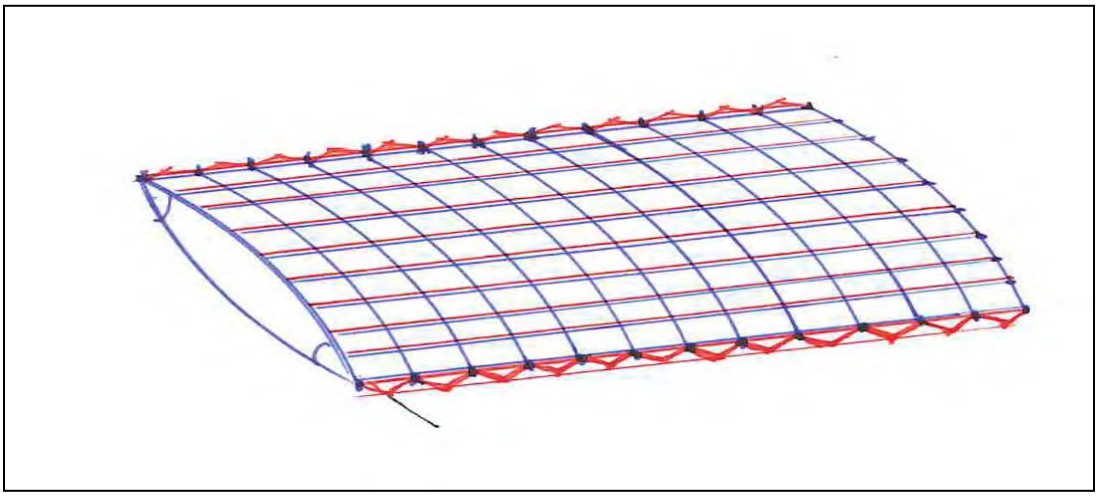

Figure 7.12 Enveloped Iceberg 0.5 km length, in a Giant Slipped Megabag Scale 1:10,000

As in the first wrapping process described in the previous section, the megabag could be slid along the iceberg using the same procedures. It could be slipped along the iceberg by the use of a boat and could be manoeuvred so as to be slipped around the iceberg (Figure 7.13. This technique has been discussed by Spragg (2001; 2006) and Spandonide (2006).

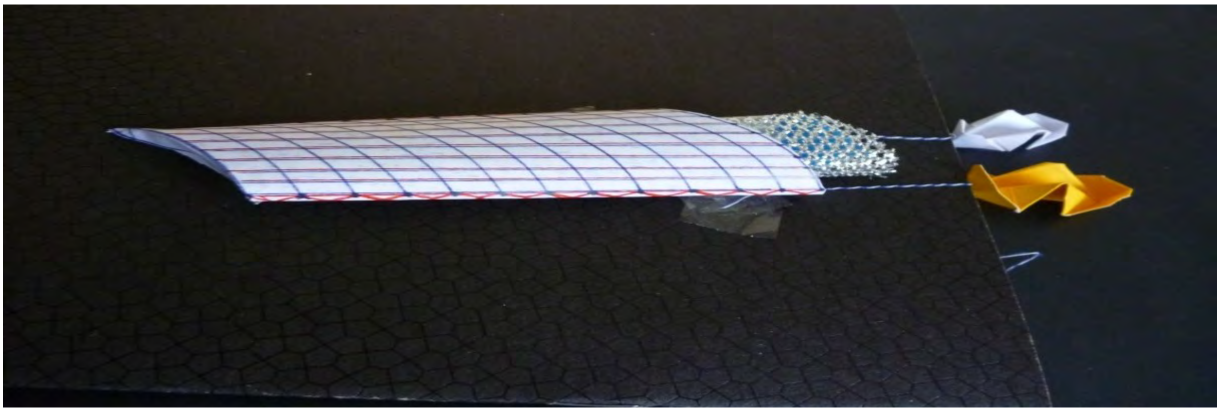

Figure 7.13 Scale Model of a Giant Slipper Megabag Filled with Air Under Low Pressure, before Enveloping the Tabular Iceberg, Towed by Two vessels. 0.5 km Length

It could also be slid along the iceberg surface using the internal net as rail system facilitating the handling of the megabag. The megabag could then be slipped along the iceberg and closed like for a sleeping bag. The megabag would have to be accurately designed according to specific geometrical and technological considerations. The megabag would have to be flexible. A pillow membrane container would be suitable to match the shape of the iceberg and its foam-layered sheet. In the case of an iceberg under 25 million t, the pillow membrane of the bag would extend below the waterline by 135 m and would protect the submerged part of the iceberg. This semi-rigid megabag could also be attached to the inner structure with rivets that compress and hold the iceberg during the melting process. This equipment would assist in maintaining the stability of the iceberg during melting and transportation (Figure 7.14).

Figure 7.14 600 GL Capacity 2 km Diameter Megabag with the Encapsulated Iceberg Scale Model

In both cases of megabag sliding around the sides of the iceberg with weights and closed with a zipping system and megabag slipped along the iceberg (both either with a boat or a ROV or with a railing system), the bag would have connectors inserted inside the rails of the internal net. The sheet of the megabag would then be tightened on the top of the iceberg using the winch or the rivet system. The sheet would let the melt water to pass through it into the collar.

Several techniques and devices such as welded seams, seals, caps, corks or zippers, have been studied for closing and sealing the bags. Sobinger (1986) developed a method using welding techniques that could be used. The strength of the welded seam (PVC sheeted woven foil tensile seams) depends on the ambient temperature during the welding (Sobinger, 1986). When using the sliding zippers technique, the zippers could be driven automatically and remotely by using a pneumatic or radio controlled slider or a sonar-controlled slider (Spragg, 2001; 2006). The studies undertaken by Sobinger (1985) provide precise methodological details on different types of materials used for wrapping. Based on his work, new studies could be undertaken.

As noted previously, the appropriate iceberg for this proposal would have a volume ranging between 25 million t and 100 million t. Hult and Ostrander (1979) noted than wrapping of an iceberg could be performed at a rate of 100 to 300 hrs/km. A crew of 15 persons would take three days to wrap a 25 million t iceberg (500 m long, 300 m deep and 150 m wide).

The evolution of the shape of the megabag during the melting process and the stability of the iceberg could be monitored with a remote sensing system (Mellor, 1985; Sobinger, 1986; C-CORE, 2004; 2007[27]). Hult and Ostrander (1978) and Moore (1978) used a system of microwave transducers to track the icebergs variable geometry during melting. In their experiments Eik *et al.* (2010) used a QualiSysTM motion system.

7.3 Collar Installation and Connection

The iceberg encapsulated in the megabag would be encircled by an expandable collar that would collect and contain the melted water. A temporary offshore collar would be attached to the megabag by means of a geodesic structure. The collar would be attached to a structure by a concentric network of circular and radial rails (Figure 7.15 and 7.16).

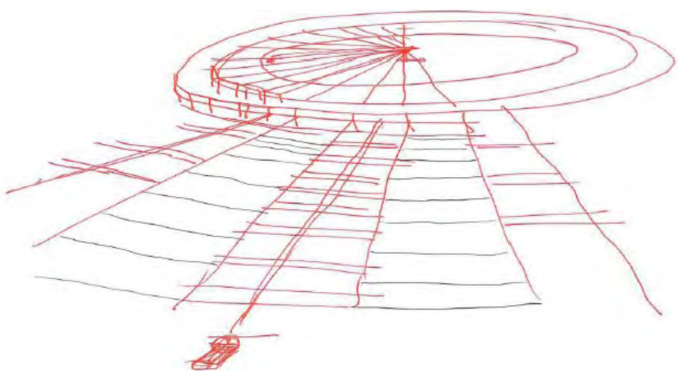

Figure 7.15 Iceberg Collar and Bag Deployments. Conceptual Sketching Collar Diameter 1 km. Scale 1:50,000

[27] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Oceans_Iceberg_Profiles_04.pdf and ftp://ftp2.chc.nrc.ca/CRTreports/GB_Iceberg_Manage_Overview_07.pdf

Figure 7.16 The Scale Model of the Collar and the Megabag Surrounded by a Geodesic Structure Bottom View. Collar Ray 2 km. Scale 1:50,000

The cells delimitated in this network would allow melted water collection and storage. The collar would expand naturally at the waterline as the iceberg melts. The collar would be designed like an accordion (Wakeford, 2008), composed of expandable ballast disks (like the pressure system of an expandable Tupperware). The collar would be filled with freshwater through pipeline gates. The freshwater would flow from the megabag to the collar because of a pressure gradient between the bag and collar; the melted water would be collected at the waterline, as the density of the melted water is lower than that of the sea water density. This phenomenon is explained by Pascal's principle on fluid mechanics. It states that "a change in the pressure of an enclosed incompressible fluid is conveyed undiminished to every part of the fluid and to the surfaces of its container" (Encyclopædia Britannica, 2010[28]).

The collar would be equipped with zippers, corks, seals or other types of devices (for instance the zipper model developed by Spragg (2001[29] and 2006) to close and secure the waterproof structure for freshwater storage. The collar would be installed around the megabag for simplifying the operations of loading of the melted water into the waterbags net (Sobinger, 1986; Hewlings, 1989; Fuerle, 2003; Shick, 2004; see also Figure 7.17).

[28] Encyclopædia Britannica Online. 12 Nov. 2010
http://www.britannica.com/EBchecked/topic/211272/fluid-mechanics
[29] www.waterbag.com/

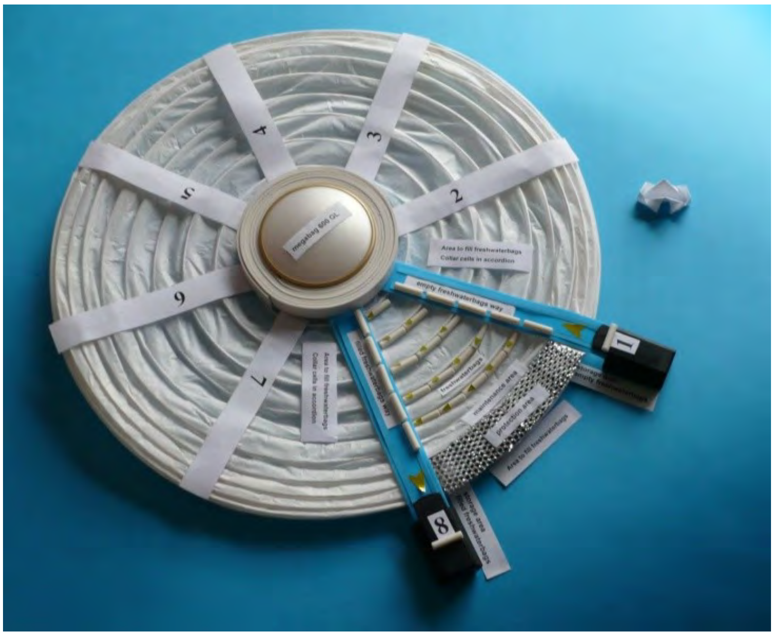

Figure 7.17 Scale Model of the Iceberg Encapsulated into a 2 km Diameter Megabag and 6 km Diameter Collar Concentric Network for Melted Water Cells. Collar. Scale 1:50,000
Legend: the expandable collar is divided into eight zones, noted 1 to 8. Each zone has two radial ways, one for empty freshwater bags and the other for filled waterbags. In the zone delimited by the ray 1 and 8, the waterbags are represented as small white cylinders. The arrows schematise the monitoring equipment and the displacement direction of waterbags. The cells delimitated by the collar radial and circular network would allow melted water collection and storage. These cells would be connected to the waterbags contained in the collar. On the peripheral zone of the collar there would be a protection area against the waves erosion. A maintenance zone is located between the protection area and the freshwater loading area. At the end of each ray (ex 1 and 8) are storage areas, represented by the black rectangles, for waterbags, empty or filled with water.

The melted water would pass into the collar. A limited amount of fresh water could stay in the megabag without affecting the equilibrium of the iceberg (Hult and Ostrander, 1973). This amount could vary between 0.2 m and 2 m pockets of water in the envelope surrounding the surrounding, in order to increase the heat transfer. Special reinforcements would be needed to minimise the effects of friction on the sides and corners of the bag (Hult and Ostrander, 1973). The collar would contain built-in inside its own structure numerous detachable waterbags (17,000 t) in which the melted water would be transferred thereby avoiding the need to manoeuvre huge quantities of freshwater in a single enclosed volume. Melted freshwater transfers from the megabag encapsulating the iceberg to the attached offshore collar would progressively reduce the size of the megabag and expand the collar. The continuous transfer of fresh water would enhance stabilisation by allowing the megabag to adjust to the evolving shape of the iceberg and the different forces acting on the iceberg to seek equilibrium, thereby reducing the risk of the iceberg capsizing. Acting like a floating boom, the collar would reduce the amplitudes of ocean waves, during wrapping. The collar would help to stabilise the iceberg during the melting process by exerting pressure around it and absorbing a part of the waves pressure at the surface. Figure 7.18a shows a scale model of the Megabag and its collar compared with different tabular icebergs.

Figure 7.18a The Scale Model of the Megabag and its Collar Compared with Different Tabular Icebergs. Collar Length 1 km. Scale1:50,000 (Spandonide 2009 on photo Walk 2000[30])

Details of the collar are shown in Figure 7.18b. This simulation corresponds to the stage in which the iceberg has melted substantially and the collar is part full. Based upon information supplied by Sobinger, (1985), it is likely that the iceberg megabag and collar would last between 10 to 15 years.

Figure 7.18b Iceberg and Collar Netting

[30] http://commons.wikimedia.org/wiki/File:Iceberg_18_2000_08_12.jpg

7.4 Iceberg Melting and Water Collection

The time the collar would take to be filled with freshwater is a function of the melting rate of the iceberg. In previous projects, bags were mainly specifically designed with thermal conductivity features against melt. In our project bags would be designed with thermal conductivity features in order to enhance melt. To improve the rate at which the bagged iceberg melts, the iceberg megabag could contain thermal heating features (Kazlousky, 2010[31]). As noted in Chapter 3, iceberg melting occurs naturally both in laminar and turbulent regimes (Donaldson, 1978[32]). Local heat transfer coefficients induced by the iceberg displacement are correlated with melting rates (Hult and Ostrander, 1973; 1978; Mougin, 1981; Sobinger, 1985). In 2010 the 3DS team undertook a digital hydraulic simulation of a new iceberg transportation project from Mougin using the SIMULIA Abaqus software to assess the iceberg melting and to evaluate with a thermal mapping of the heat exchanges the iceberg melt, reproducing the ocean conditions, the speed and temperature of the sea currents and winds (3DS, 2010).

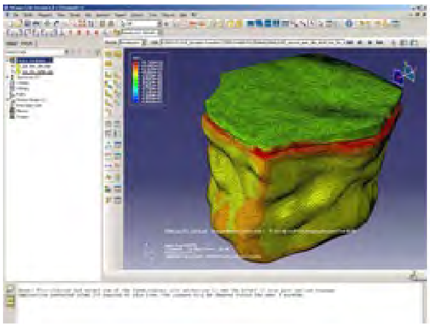

Figure 7.19 Iceberg thermal mapping (credit 3DS, 2010[33])

It can take a long time for an iceberg to melt. According to Hult and Ostrander (1973), giant tabular icebergs can take up to five years to disintegrate completely, as the rate of melting is inversely proportional to the volume of the iceberg. However the melting rate would increase with greater heat convection from sea water, melt water and air as well as from wave action and solar flux (Chapter 3). Figure 7.20 shows iceberg melting induced by the increasing atmospheric temperature.

[31] http://www.wipo.int/pctdb/en/wo.jsp?WO=2010099797
[32] http://www.nature.com/nature/journal/v275/n5678/abs/275305a0.html
[33] http://perspectives.3ds.com/environment/how-to-tow-an-iceberg-pt-1/

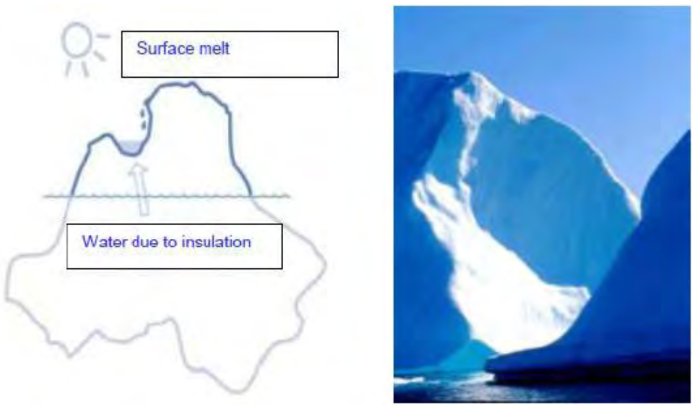

Figure 7.20 Iceberg Melting Induced by Increasing Atmospheric Temperature - Schematic Representation on the Left and Real Image on the Right (credit Walk[34], 2000)

Iceberg melting rates are directly affected by the temperatures of the sea water in which they are floating (Veihelmann *et al.*, 2001). In sea waters of around 15°C, it is realistic to expect around five months for complete melting of an iceberg of 25 million t. (Hult and Ostrander; 1973, Sobinger, 1985). Near Kerguelen Island, over a distance of 450 km between latitudes 50° S to 46° S in summer and 42° S to 38° S in winter, the average sea temperature can change from 7°C to 14°C The solar heat flux amplitude would be around 60 W/mK for a 1 million t iceberg (Budd, 1980). An iceberg originating from the Amery Ice Shelf which would have drifted 1,000 km eastward, could be transported 600 km to warmer waters, east of the Kerguelen Islands at around 48° S in order to increase the melting rhythms. Melt rhythms for a 100,000t iceberg would be around 0.5%/day or for a 100 m long iceberg about 0.5 m/day (Lefrançois *et al.*, 2008[35]). Hult and Ostrander, (1973) noted that this is the range of natural melting rates. There would also be icebergs originating from the Ronne Ice Shelf, 5,000 km away. Melting in stable conditions of sea and air temperatures (with air temperatures above sea temperatures) and waves could be controlled. Melting would occur at the surface water line where the netting system would be reinforced. Melting the iceberg in such conditions would occur continuously (Sobinger, 1985). It would decrease risks of capsizing.

Hult and Ostrander, (1973) noted that the transportation of a melting iceberg in its bag could enhance breakage and capsizing risks. Sobinger (1985) demonstrated that a 300,000 t iceberg could be melted without breaking in a megabag. This suggests that the transportation of the melting iceberg could therefore be jeopardised by stability issues

[34] http://commons.wikimedia.org/wiki/File:Iceberg_16_2000_08_12.jpg
[35] http://ltte.gmc.ulaval.ca/Publications%20(va)%20-%20LTTE.html, see also http://www.tcsme.org/Vol32-No3-4.html

whereas the transportation of the water of the iceberg fully melted would be feasible (Huppert, 1980). In order to minimise stability risks, a second netting system could be used to decrease capsizing risks and once the iceberg melt is completed its water could be transported in specific bags.

7.4.1 External Netting

The external netting system is a flexible holding structure equipped with wire screen reinforcements designed to enhance the transfer of water from the bagged iceberg to the collar and to transport the bagged iceberg and its collar. The external netting system could be used as the technology recommended by Ocean Ltd (2004[36]) for icebergs harnessing (Figure 7.21). Figure 7.22 shows an example of netting for harnessing of small icebergs as commonly used by the Iceberg Vodka Company.

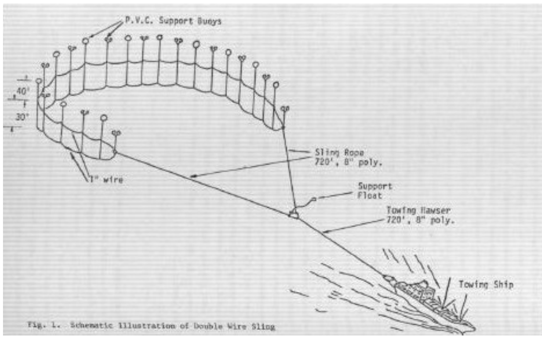

Figure 7.21 Iceberg Being Towed by a Tug (credit Husseiny, 1978 in Bowring *et al.*, 2010[37] n.p.)

Figure 7.22 Iceberg Vodka Iceberg Water Harvesting (credit Power *et al.*,[38] 2004 n.p.)

[36]ftp://ftp2.chc.nrc.ca/CRTreports/GB_Iceberg_Manage_Overview_07.pdf
[37]http://web.mit.edu/12.000/www/m2012/finalwebsite/solution/glaciers.shtml

A second netting system would be installed around the iceberg and its sheet by a vessel, as for the internal netting system. This external netting system would help to maintain a steady air pressure between the collar and the megabag. A dymaxion semi rigid net structure encasing the iceberg and the collar could further secure the iceberg stability (Spandonide, 2009). For the external net a force of 300,000 pounds would be required to sustain the pull of the giant kites providing directions to the iceberg megabag. The megabag with 30 attachment points would be able to sustain this pull. Such nets would need further testing.

The winch rivet device would progressively tighten and compress the net around the bagged iceberg, its megabag and its collar allowing the net to adjust to the changing geometry of the bagged iceberg during melting and its collar. The external netting system would help manoeuvring the bagged iceberg and its collar. To work out the problems generated by the instability during melting, the iceberg wrapped in a megabag would start to melt. The melted water would be withdrawn from the megabag and collected progressively and continuously in a collar. This pressure could enhance the transfer of the melting water in the collar. The compression force exerted by the internal net on the iceberg would be higher than the pressure of the melting water acting on the bag. Once transported in warmer waters, the iceberg would start to melt and its water would be transferred into the collar. The net would then be used to adjust the shapes of the iceberg megabag and the collar to the changing shape of the melting iceberg and its melted water.

The bagged iceberg size would be progressively reduced while the size of the collar would be expanding progressively. The fixed compression force exerted by the external net would allow to transfer this force on the iceberg megabag via the pressure exerted by the expanding collar on the bagged iceberg. This pressure would fit together both the expanding collar shape to the melting bagged iceberg.

The behaviour of the iceberg transported during its complete melting would cause higher risks of capsizing and therefore of stress. It is not likely that any netting system could hold continuously the amount of stress caused by a complete breakage or the capsizing of a tabular iceberg; a netting system with several million pounds capacity would be necessary. Therefore the option to transport the iceberg on limited distance and time and then to melt in its bag would hold less technical uncertainties.

[38] http://www.icebergvodka.com/

7.5 Manoeuvring

There are two main components of iceberg water manoeuvring: movement of the iceberg from the capture zone to a warmer zone and manoeuvring of the iceberg water in waterbags.

7.5.1 Bagged Iceberg and Collar Manoeuvring

In our project, the offshore system comprising the iceberg which would have been encapsulated into the megabag, the collar and the freshwater bags could be manoeuvred using techniques similar to those described by Hult and Ostrander (1973), Benedict (1978), Bosma (1979), Mauviel (1980[39]), Sobinger (1985), Rowden-Rich(1986), Spragg (2001), Ocean Ltd. (2004; 2007[40]), PERD/CHC, (Report 20-84, 2007), Eik *et al.* (2010) and Skysails (2011). Two options can be considered for the manoeuvring of icebergs: the deflection with a tug boat and the deflection with kites. For the tug option, when an iceberg is detected and considered to be optimal for transportation, then it may be deflected into a safe direction by means of vessel towing in about 75% of cases as identified in Chapter 6 (Rudkin *et al.*, 2005). It appears that the iceberg towing vessels designed for large iceberg ocean towing for deflection purposes would need a minimum bollard pull of 50 tons. As mentioned in Chapter 6 other equipment consists in: a handling towing winch, a towing hawser, long distance (800 m) search lights, anchors, tension gauge monitoring systems (like a Martin Decker Dynaline tension meter), floating synthetic towlines, messenger line with buoys at the end.

Towing small icebergs with a tugboat has been tested since 1978 (Benedict, 1978; Bosma, 1979; Mauviel, 1980[41]; PERD/CHC, Report 20-84, 2007). Sobinger (1985) experimented towing on small icebergs but did not have the time and funding to study towing of large bagged icebergs. Towing experience of large Antarctic icebergs is almost inexistent and experiences gained on the Grand Banks off Newfoundland or from towing experiments of Sobinger or Mauviel, are useful to understand the technological complexity of such a towing process in Antarctica (See Appendix 6). However, it was demonstrated that dual vessel towing is able to direct masses larger than 1 million t (PERD/CHC Report 20-84, 2007). These Canadian experiments did not focus on towing for transportation purposes but on towing for deflection purposes. The deflection operations should occur in calm high sea state

[39] http://www.igsoc.org/annals.old/1/igs_annals_vol01_year1980_pg123-127.pdf
[40] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Oceans_Iceberg_Profiles_04.pdf, ftp://ftp2.chc.nrc.ca/CRTreports/GB_Iceberg_Manage_Overview_07.pdf
[41] http://www.igsoc.org/annals.old/1/igs_annals_vol01_year1980_pg123-127.pdf

conditions, for a successful towline deployment. The towing strategy would then involve several steps (PERD/CHC, Report 20-84, 2007): The vessels crew would assess the dimensions of the iceberg and its mass with side scans, calculating the speed of the iceberg and would chose a stable iceberg by calculating its instability (draft versus hieght). According to Eik *et al.* (2010) "variations in speed, acceleration, course and iceberg shape seem to be less important" than momentum when drifting. An Iceberg maintains a straight course even with significant pressures placed on it to change its course. Therefore it is difficult to change the direction of the iceberg. For large stable icebergs (> 300 m diameter) indent would be made around the waterlight and 3 sections of 400 m of towlines for three vessels would be passed around the iceberg. A heaving line would be passed between the three vessels and the hawsers would be connected using a swivel and shackles. The sections would be passed over the stern, run off shackled and paid out behind the tow vessels. The vessels would circle the iceberg and the last end of the tow sections would be fastened to the eye in the fishplate already fastened to the steel hawsers. The tow force would be brought closer to the iceberg's center of gravity using the steel hawser catenary to reduce overtunrning movement (Bosma, 1979; PERD/CHC, Report 20-84, 2007). Towing force has to be exerted through the centre of mass of the iceberg. The free end would be grappled, recovered and connected to the fish plate (Bosma, 1979). The three vessels would go on either side of the iceberg keeping a small amount of tension on the hawser until contact would be made with the iceberg (Figure 7.23).

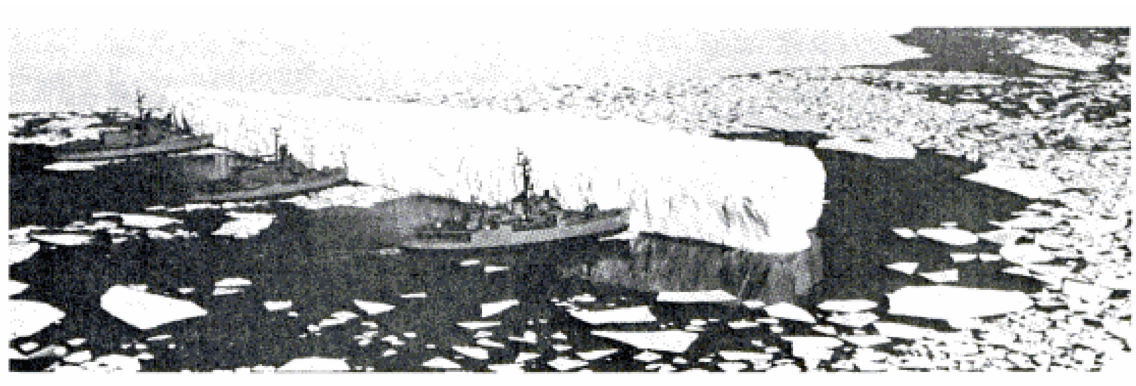

Figure 7.23 Three Icebreakers Push An Antarctic Iceberg near McMurdo Station. Their Combine Efforts moved the Berg 2.5 miles in 12 hours (credit Weeks and Campbell, 1973 p 35)

The tow could be optimised by deploying the towline on the lee side of the iceberg (Bosma, 1979). When tightening an optimal timing (30 seconds) would help as well. Full towing power would be applied after a long period with vessels holding their position and maintaining headings 15 degrees apart. The stability issues of the iceberg would need to be studied specifically for the intended iceberg deflection routes. A proposed solution would be to reinforce the iceberg's stability by the use of the internal netting system. The encapsulated iceberg in the megabag could be deflected first with vessels, and then kites, as described by Skysails (2008; 2011), and would follow the currents to make a maximal use of them. In this project the deflection of iceberg would also be provided by kites whereas the main moving force would come from the currents. The natural drift would slowly transport the iceberg into warmer currents in order to speed up the melting process. The collar could be either transported attached to the iceberg as it won't be in an expanded stage, or installed on the megabag after the arrival of the bagged iceberg in this warmer zone. The choice would depend upon expected weather conditions, towing process, or expected melting rates. If an iceberg drifts freely in a current then it may be assumed that it partakes the same motion as the water it displaces. No forces appear or are required unless the iceberg is moved relative to the current. The model is dependent on the currents, winds and temperature and on the route selected. At very low speed, the currents would be the strongest transporting force and the winds action would be the strongest deflection forces. These forces would depend on speed and thrust angle which are function of latitude, iceberg size, shape, force coefficients and thrust of wind and currents. Eik *et al.*, (2010 [42] p.3) demonstrated that the load magnitude of a small iceberg (less than 20,000 t): "in open water would maintain momentum straight ahead even after a course change and the sideways displacements (sway) would be significant. Heave motions are negligible". According to Hult and Ostrander (1973) at low speed, the wavemaking resistance is minimal for elliptically shaped tabular icebergs. The two main acting forces would be the skin friction and the drag coefficient corresponding to the water displaced by the moving iceberg would flow around and under the iceberg. Hydrodynamic drag results from the disturbance of flow around an object and is composed of the form drag coefficient, related to Reynolds number and the cross-section of the object, depending on the shape and on the related re-distribution of the pressures on the surface of the iceberg (form drag = 0.5 x (density of fluid) x (form drag coefficient) x (cross-section area) x (velocity of object)^2), the friction drag coefficient, related to Reynolds number and the nature of the object's surface, depending on the roughness of the surface over which the fluid is flowing (friction drag = 0. 5 x (density of fluid) x (friction drag of object coefficient) x (total area) x (velocity)^2) and the wave resistance, related to the Froude number and the shape of the water line, depending on the interaction between wave fronts from the bow and the stern of a floating object (wave resistance = (density of water) x (wave resistance

[42] http://www.hydralab.eu/proceedings/HSVA-8_Eik.pdf

coefficient) x (displacement of object) x (acceleration due to gravity)) (Mauviel, 1980[43]). At speeds below the wavemaking limit, the principal resistance is the skin friction. The form drag is likely to dominate the skin friction for tabular rectangular icebergs. Normal and tangential drag forces, dynamic pressure forces and skin friction are parallel and perpendicular to the axis of the iceberg. These forces depend on the density of ice, the iceberg mass, the iceberg size and characteristics, the relative speed and the sea water density. Depending on the length (for length/width = 5) and speed of the transported bagged iceberg the skin friction coefficient based on wetted area and a maximal frontal cross section of 0.04 could be around 0.003 (depending on length and speed) and the drag coefficient could be around 0.1 (Hult and Ostrander, 1973). As the transportation of the iceberg would occur at low speed, the Coriolis forces would dominate. Elliptical shaped bagged icebergs would have a shape which would minimise the Coriolis force and displaced water resistance. Mauviel (1980) found turbulent flow conditions form drag coefficient of 1.14 for his model and the friction drag represented 9% of the total drag, wave resistance remaining negligible for Froude numbers below 0.018, which corresponds to a towing speed of 3.6 knots for a 1,000 m long iceberg taking into account the effects of the narrow dimensions, and the inertia correction. Reynolds similitude was not achieved as the speeds needed were too high for the model, the flow had reached its turbulent state. The critical Reynolds number value appears to be 5×10^5. During the high Reynolds number tests (5×10^6), no waves appeared at the bow of the model, a very light wave appearing when the outboard engine supplied its maximum thrust. These coefficients are a function of the angle a between the model velocity and its main axis, and the angle between the towing force and the main axis are related by a = $\tan^{-1}$ (0.5 tan b). These drag coefficient corresponds to objects with poor drag profiles (Hoerner 1965). The lozenge shape was the easiest to tow with an achieved speed of 0.25m/s (for a Froude number of 0.018) and again no wave resistance on a 1,000 m fullscale iceberg with speeds below 1.8 m/s. Propulsion at low speeds with artificial and natural forces located in front of the centre of gravity was the most efficient. A component of the deflection forces must be used to compensate for Coriolis forces (Hult and Ostrander, 1973). The magnitude of the Coriolis effects depend upon the magnitude of the velocity vector, thrust angle, and the dynamic pressure of winds and currents (which would be similar to water drag effects), and are proportional to the mass, earth rotation, and the latitude. They would provide the main resistance to the deflection operations and would require a substantial part of the transport effort to counteract or to use their effects particularly at more southerly latitudes (Figure 7.24).

[43] http://www.igsoc.org/annals.old/1/igs_annals_vol01_year1980_pg123-127.pdf

$$F_c \text{ (parallel)} = 2mV\Omega \sin \varphi \sin \beta \ , \qquad \text{(D-1a)}$$

$$F_c \text{ (normal)} = 2mV\Omega \sin \varphi \cos \beta \ , \qquad \text{(D-1b)}$$

where m = mass,

Ω = earth's rotation (7.29×10^{-5} rad/sec),

φ = latitude (negative in the Southern Hemisphere),

V = speed,

β = thrust angle.

A parallel force component is positive if it acts with the thrust vector (+y direction); a normal force is positive if it acts in the +x direction. With these conventions, β will be a positive angle when propelling in the Southern Hemisphere.

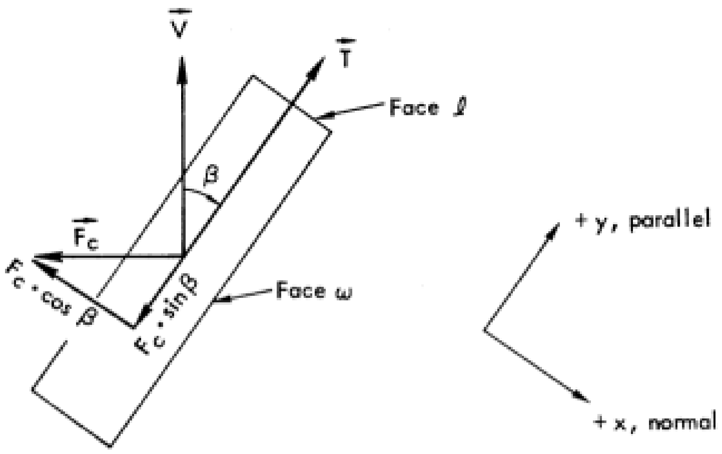

Fig. D-2 — Coriolis Force Components

Figure 7.24 Coriolis Force Components (credit Hult and Ostrander, 1973[44] p. 46)

[44] http://www.rand.org/pubs/reports/2008/R1255.pdf

It can be assumed that surface drift currents extend to a depth of up to 150 m (Hult and Ostrander, 1973). Deeper currents would not differ substantially from surface drift currents in the acquisition region. The forces and directions of the wind deflection force should be evaluated (respectively in Beaufort and in a percentage of time of blow). The wind roses of pilot charts provide average wind direction, force and frequency information as well as drift current direction (Hult and Ostrander, 1973[45] p. 41). The deflection from the vessel or the kites could use the external net as a harnessing system for deflection. Deflection techniques cause less stress to icebergs, and reduce breaking risks. Eik *et al.* (2010[46] p.3) found that to move even small icebergs:

> The effects of pitch and roll were negligible and stability was not a concern. The static friction between tow ropes and an iceberg under tow are relatively high, thus a change in the tow direction can also cause the iceberg to yaw.

According to Eik *et al*. (2010), log-normal distribution functions are effective to simulate the tension forces applied on icebergs under tow. The studies conducted by Eik *et al*. (2010) focused on towing icebergs in four different ice concentrations. They used relatively small icebergs, and it remains uncertain if the results could be applicable to understanding the stability of tabular icebergs of significantly increased size. However, small icebergs tend to be more unstable than large icebergs (Sobinger, 1985). The above water shape of the iceberg plays an important role in the instability of the iceberg (McClintock *et al.*, 2007).

It is estimated that a force of 20 million pounds would be necessary to propel effectively a 25 million t iceberg. This force would correspond to a power several hundreds of GW. However for deflection purposes, 50 GW would be enough to change the direction of a 25 million t iceberg (Hult and Ostrander, 1973; Sobinger, 1985). A very large kite could produce a pulling force (lift and drag) of between 5 and 20 GW (Skysails, 2006; Kiteship, 2010). To improve the efficiency of an iceberg transport system, it would be important to determine the optimal deflection angle of the propulsion force of the iceberg transportation, with experiments which would help to determine uncertainties of Coriolis and Polflucht effects. Table 7.1 indicates the forces required to tow and to steer an iceberg and corresponding waterbags for several speeds. It will be used as a basis for the economic evaluations (Chapter 10).

[45]http://www.rand.org/pubs/reports/2008/R1255.pdf
[46]http://www.hydralab.eu/proceedings/HSVA-8_Eik.pdf

Table 7.1 Icebergs and Waterbags Steer and Towing Forces at Various Speeds

Iceberg Size	Speed	Operation	Force Pounds	Force GW
100 million t	2 km/h	Towing	5,000,000	200
		Steering	2,000,000	80
		Bags	2,000,000	80
	Speed 0.7 km/h	Towing	1,000,000	40
		Steering	400,000	16
		Bags	400,000	16
25 million t iceberg	Speed 2 km/h	Towing	1,250,000	50
		Steering	500,000	20
		Bags	500,000	20
	Speed 0.7 km/h	Towing	250,000	10
		Steering	100,000	4
		Bags	100,000	4
8 million t iceberg	Speed 2 km/h	Towing	400,000	16
		Steering	160,000	6.4
		Bags	160,000	6.4
	Speed 0.7 km/h	Towing	80,000	3.2
		Steering	32,000	1.28
		Bags	32,000	1.28
1 million t iceberg	Speed 2 km/h	Towing	50,000	2
		Steering	20,000	0.8
		Bags	20,000	0.8
	Speed 0.7 km/h	Towing	10,000	0.4
		Steering	4,000	0.16
		Bags	4,000	0.16

Skysails currently proposes 5,000 kW kites (Chapter 6).

7.5.2 Melted Water Manoeuvring

Melted water would then be transported to Perth (37° S), a distance of 1,400 km, in small waterbags. Water transportation in relatively small waterbags has been studied by waterbag companies as discussed in Chapter 6.

7.6 Waterbag Design

To transport the melted water of the iceberg numerous small waterbags (20,000 m^3) would be attached to the collar to be loaded with iceberg melted water as shown in Figure 7.18. Waterbags can have different capacities. Spragg designed a modular bag 50 m in diameter and 160 m long with a capacity of 17,000 m^3 (Spragg, 2001[47]). The Aquarius bag, which is 200 m long, 30 m wide and 10 m deep, can hold a volume of water equivalent to 60,000 t. The Medusa bag or the bags used by the company Nordic Water Supply are as large as 650 m long, 150 m wide and 22 m deep, with a capacity of around 100,000 t[48]. In order to maintain control of the current drift and maximise the use of kites, the optimal size of bags used in this project would be between 20,000 m^3 to 40,000 m^3.

For river or calm sea transportation, the material used in the construction of waterbags consists of a highly durable fibre-reinforced elastic polyester (polyurethane) coated with plastic (Spragg, 2001; NWS, 2005). It is lightweight and flexible and has a thickness of between 1 and 2 mm. The Spragg waterbags wrapping envelope, for example, is made from a 1 mm thick reinforced plastic membrane and has a dry weight of 20 t (Spragg, 2001). The materials are flexible. The bags could be built with stress-diffusing straps, which could also be inflated. For ocean transportation, the bag membranes need to be at least five times thicker (Sobinger, 1985). These bags would last from seven to eight years (Sobinger, 1985; Spragg, 2001). The reliability and lifetime of these bags could be improved with experiments with new materials and maintenance technologies (Figure 7.25).

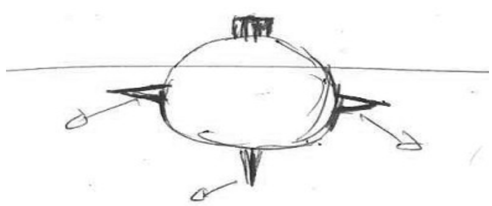

Figure 7.25 Waterbag Scale Conceptual Sketch. Scale 1:5,000 Bag 10 m

The waterbags would be towed into the currents and be driven by kites, on a drift trajectory forecast on the basis of predominant winds and currents. Compared with the existing bags described previously, in this proposal, the shape of the waterbags would be designed specifically for drifting in Southern Ocean currents. The architecture of the waterbags would

[47] www.waterbag.com/
[48] http://mhwaters.com/watertransport.html, see also www.monohakobi.com

be in agreement with the principles of fluid mechanics and the quality of new composite materials used today in the aerospace industry (Eyres, 2001). The waterbags drag coefficient (C_d), cross sectional area, and towing speed, determine the force and power required for towing (Watson, 1998). Waterbag manoeuvring at slow speeds would significantly reduce the drag friction. Gosselin *et al*., 2008 estimated the drag coefficient for a 1 million t iceberg to be 0.9. However, for a streamlined iceberg train the drag coefficient could be between 0.6 and 0.8 and for waterbags, the drag coefficient could be reduced to $C_d = 0.1$ (Sobinger, 1985; Spragg, 2001). Different bag shapes could be developed to lower the drag and diminish the skin friction at the wetted surface (Schneekluth and Bertram, 1998). Longitudinally, a sausage shape would be suitable. To prevent breaking the bags could be streamlined by shaping the fabric skin and filling the bag to a pressure slightly over the atmospheric pressure so that the bag adopts the desired shape (Eyres, 2001). For side force reinforcement, a streamlined sausage shape would provide a ratio of length to diameter that would reduce stress but increase the skin area. Bubble sheets or inflated ballast could reduce the shocks of big waves (big sea waves can exert intense pressure on bags). The waterbags would be partitioned, baffled, or filled with open-celled foam fitted with elastic reinforced stress-diffusing straps ballasts (like bubble wrap) to prevent bag rupture caused from the enormous inertia of the filled waterbag. With appropriate hydro and aero dynamic features (for example: fish tails, tapering tail or a bulbous nose), the amount of wavemaking resistance created from the bag can be reduced (Watson, 1998). The waterbag shape would optimise the natural drift into Southern Ocean currents. The Taylor Bow or the Inui Bow are widely used on large commercial ships where they typically reduce fuel consumption by about 5% at cruising speeds, and they could be applied to waterbags so as to reduce resistance. Waterbag design, including shape, lateral reinforcements, stern and bow profile, top crest, keel, and weights, can be made so as to optimise the natural drift obtained from water currents (O'Rourke, 2006[49]). Naval architecture principles could assess the distribution of the propulsion force, pressure inside the bag, acting forces of the propulsion system of the currents, durability of waterbags under different sea conditions (wave intensity and swell direction) to design appropriate hydro and aero dynamic features and optimise the wave resistance and buoyancy on saltwater (Bertram, 2000).

As suggested by Spragg (2001) a 17,000 t waterbag would be loaded with water in a minimum of 10 hours.

[49] http://www.fas.org/sgp/crs/weapons/RL33360.pdf

7.7 Transportation Logistics

Two scenarios are considered for the transportation of waterbags from the AAT to Perth, or other predetermined destinations in Australia. The first is to release in the Southern Ocean currents individually, a bag actioned by kites and composed from six or more waterbags. (Figure 7.26 shows a link of two giant bags of three waterbags).

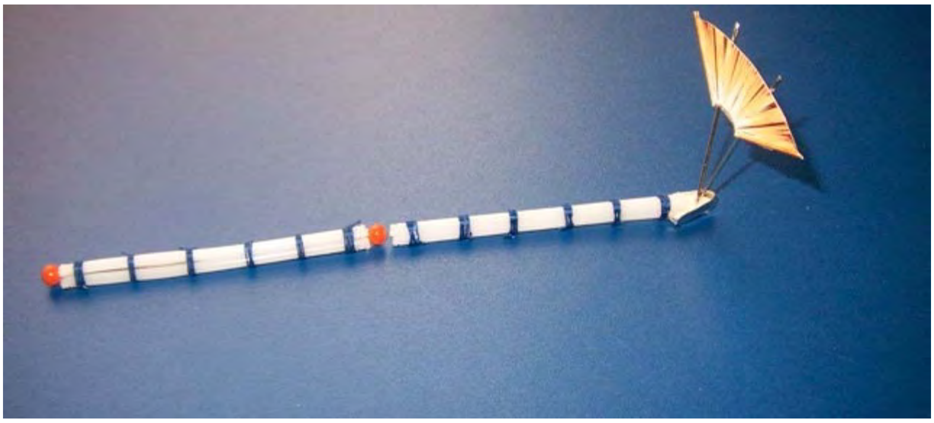

Figure 7.26 Model of the Two Links of Waterbags and a Kite. Bag Length 100 m, Train length 1 km. Each link comprises three waterbags fastened together by six belts. Scale 1:500,000

Each link comprises three waterbags fastened together by six belts. Belting three bags together would provide good equilibrium and stability of each link (about 30 m diameter) during transportation and would allow three times the volume of water to be transported (Figure 7.27).

Figure 7.27 Scale Model of a Cushion Link Composed of six Freshwater Bags of 100 m long and 20 m diameter, Kite Driven. Scale 1:50,000

After loading, the waterbags would be detached from the collar and towed to a storage zone in which the bags would be linked together and groups of freshwater bags become interdependent before launching (Figure 7.28).

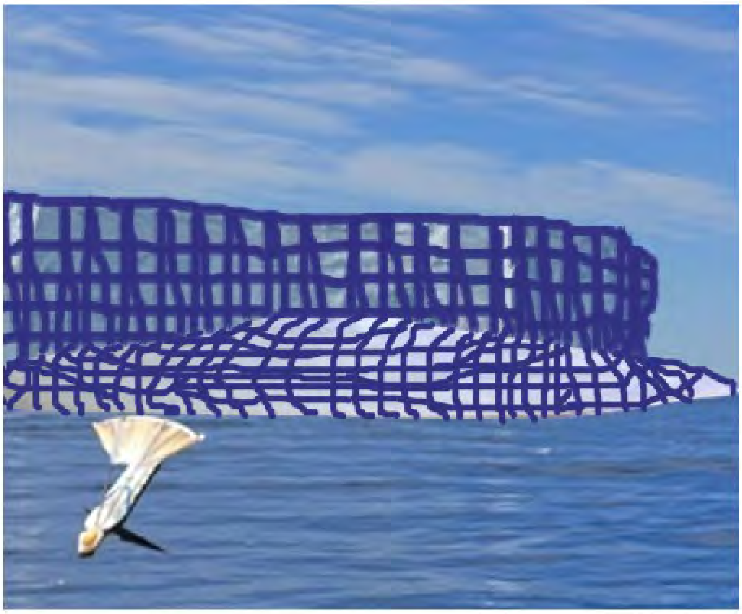

Figure 7.28 Groups of Waterbags (from Geo, 2009[50] n.p.)

The second is to form a train of 60 to 100 waterbags and to direct the train to the Southern Ocean currents under kite control. In both cases the drift trajectory would be controlled by kites and monitored by satellites (Skysails, 2008). In both scenarios the propulsion system is composed of three elements: tug boats to launch the waterbags into the currents and to retrieve them for final delivery; kites using wind energy to provide direction and orientation for individual waterbags or for a train of waterbags; and ocean surface currents to provide the basic motive force. A waterbag convoy is likely to have good stability, given that a waterbag has better buoyancy in oceanic saltwater than in river water (Edmonds, 2009[51]). This proposal focuses on a waterbag train system because of its ability to deliver larger quantities of freshwater (Hult and Ostrander, 1973).

7.7.1 Train of Waterbags Assembling Process

[50] http://www.geo.fr/voyages/vos-voyages-de-reve/georgie-du-sud-la-traversee-par-les-sommets/iceberg-a-l-horizon
[51] www.waterengineeringaustralia.com.au/pdf/wea_0809.pdf

According to Hult and Ostrander (1973), the maximal 20 km length and 600 m width of the train of waterbags, is economically and technically efficient. Beyond these limits the costs of transportation would increase proportionally to the increase in size. For linking the waterbags could be assembled three by three like for a catamaran, standing as three parallel floaters.

The catamaran system would have a central transporting element (a waterbag) balanced by two smaller waterbags on each sides. Special lever arms structures would have to be designed to support for the catamaran-like linkage between the waterbags (Figure 7.29 and Figure 7.30).

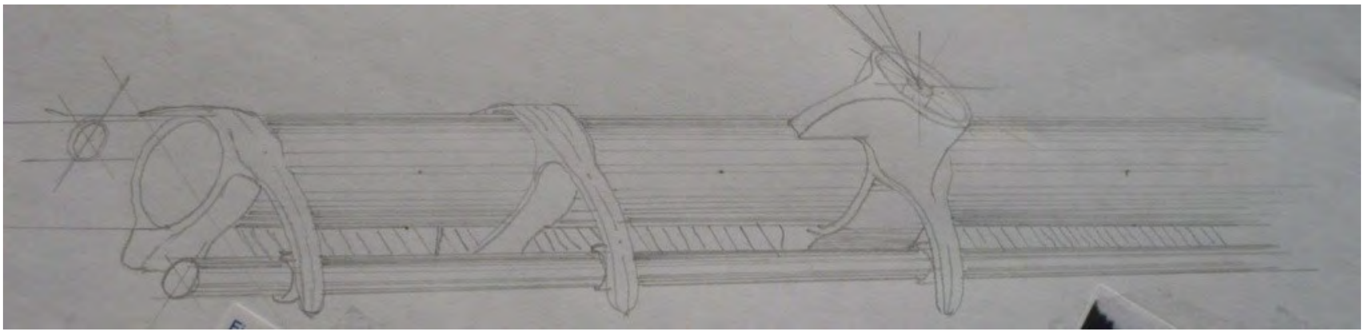

Figure 7.29 Train with a Catamaran System of Waterbag design. The central section is balanced by two attached side sections

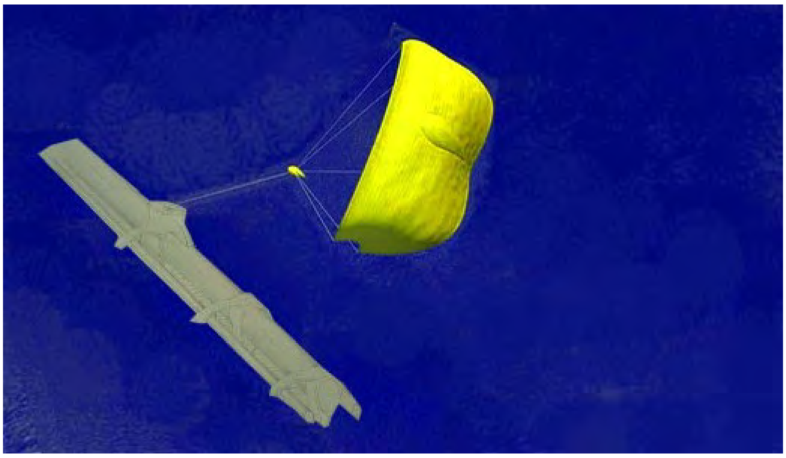

Figure 7.30 Train with a Catamaran System of Waterbag and a Skysails Kite System (readapted from Skysails GmbH&Co.KG 2004[52] n.p.)

[52]http://gcaptain.com/wp-content/uploads/2008/01/kiteship.jpg

For the train, Spragg (2001) proposed a special design of the interconnection system between the freshwater bags. The watertight elastic inter-connection system (comprising a closed envelope interconnecting the front and the back parts of two successive bags) would reduce the tensions induced by the differential movements of undersea currents and sea waves. A 'zipper' connection could be used to distribute the towing force evenly around the circumference of the bags. According to Spragg (2004[53]) "the zipper connection distributes the towing forces around the circumference of the bags". Connecting bags together using sliding zippers driven remotely could work with different systems including systems driven by pneumatic force, automatically radio controlled sliders, or sonar controlled sliders (Spragg, 2001). The existing Spragg watertight elastic inter-connection system provides an excellent model and could be used in the proposal under consideration here. This design together with waterbag coating materials would enable the convoy to handle pressures in excess of 1,000 pounds/inch^2 in both longitudinal and transverse directions. This type of bag arrangement would sustain the pull of large kites. However, for the control of the train displacement, specific sailing features would be needed which are not detailed in the Spragg system. It could be improved by doubling or tripling the number of bag trains on their width. A catamaran net distributing the forces of waves, currents and kites was suggested by (McFarlane, 2008 personal communication). An air ballast system could also improve the stability of the train of waterbags (Figure 7.31a and b and Figure 7.32).

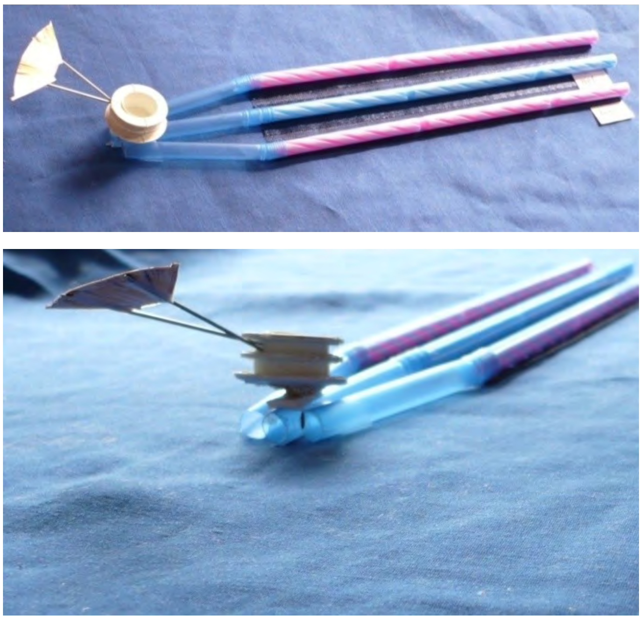

Figure 7.31a and b Waterbag Train with Stabilising Net

[53]www.waterbag.com

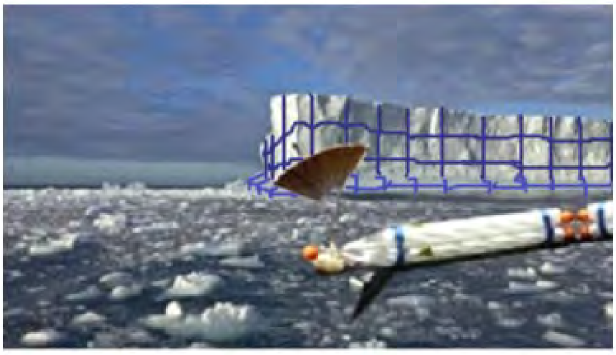

Figure 7.32 Convoy Waterbags with Deck Lever Arm Linking the Kites to the Convoy's Structure (adapted from Momatiuk, Eastcott and Minden, n.d. n.p.[54])

Once filled up with freshwater the waterbags would be detached from the collar and stored in an assembling area to form the train. The train could comprise from 60 to 100 waterbags having the capacity of 20,000 m^3/bags and interconnected in longitudinal direction with special connectors as described by Spragg (2004). This proposal for the transportation of a train of waterbags composed from 20 to 60 links was illustrated previously in Figure 7.22. The train composed of 20 to 60 links could be suitable for the transportation of 60 to 180 waterbags. For example, with a train of 60 links and 180 waterbags of 17,000 m^3, capacity each, a total of 3,060,000 m^3 (3,060,000t) of fresh water could be delivered per trip. The train would be towed to the selected ocean surface current. Surface ocean currents and winds would provide the energy for freshwater bags propulsion. Another aspect related to the successful application of this technique is the training of the crew. The crew should be trained in the fundamentals of assembling, launching, and drifting, with both theoretical and practical devices. Maritime operations training programs could be used to train the experts for iceberg transportation.

7.8 Proposed Maritime Transportation Technology

The maritime technology proposed in this system for transporting icebergs involves the launching of waterbags into currents. Their direction would be controlled by kites and monitored by satellites (Skysails, 2008). The bags would be equipped with kites that steer on the front and on the end of the train with a boat, using after the force of the currents and the wind force with the kites.

[54]http://www.webshots.com/pro/photo/3162365?path=/travel-antarctica

7.8.1 Launching into the Currents

The angle at which a train of waterbags is launched into an ocean current must be optimised as a function of the sea's physical parameters. The train launching techniques I describe below have been developed from the iceberg towing techniques, which depend on iceberg type and size described in Chapter 6.The most common technique for towing icebergs is known as "the single boat floating line tow" method (C-CORE, 2004). The tug deploys a long floating tow rope behind the boat, and then steers around the target until the tug can pick up the free floating end. The two ends of the tow rope can be connected and the main towing cable is slowly extracted until the tug is approximately 0.4 km away. At this moment the tug could slowly apply the towing force in the required direction and launch the train into the current. Currents velocity can be calculated accurately (Ifremer, 2005[55]).

7.8.2 Waterbag Drifting with the Current

The main propulsive force for the transportation of the waterbag train would be obtained from harnessing ocean currents. While ocean currents rarely provide a steady force, they can be relied upon for a continuous drift (Smith *et al.*, 2006), which can be optimised, depending on the currents, with a kite system. Currents would be the main driving force and kites would be the main means of adjusting direction. The estimated speed for the propulsion generated by maritime currents is variable but on average at the latitude and longitude where the bags would be launched it would be around 1 m/s (Smith *et al*., 2001). In order to maximise the propulsive force of ocean currents, the state of the currents in the Southern Ocean would have to be updated daily using remote sensing techniques. Such timely information would make it possible to forecast accurately the currents and the weather conditions in the Southern Ocean and to choose the most appropriate route for the waterbag train (Charlier, 1991). Weather forecasts are able to provide precise data regarding ocean current conditions. Planning a route for the train of waterbags requires information on the speed, direction and force of ocean currents and winds and the impact of the Coriolis force. Skysails elaborated a decision model process which is able to calculate the optimal routes from expected routes, speeds, and weather conditions. It maximises the performance of its kite system by determining specific waypoints. Favourable currents and winds exist in the high seas on the route from Antarctica to WA (Figure 7.33).

[55]http://www.ifremer.fr/lpo/gliders/donnees_tt/slocum/instruments/notes_techniques/calcul_courant.pdf

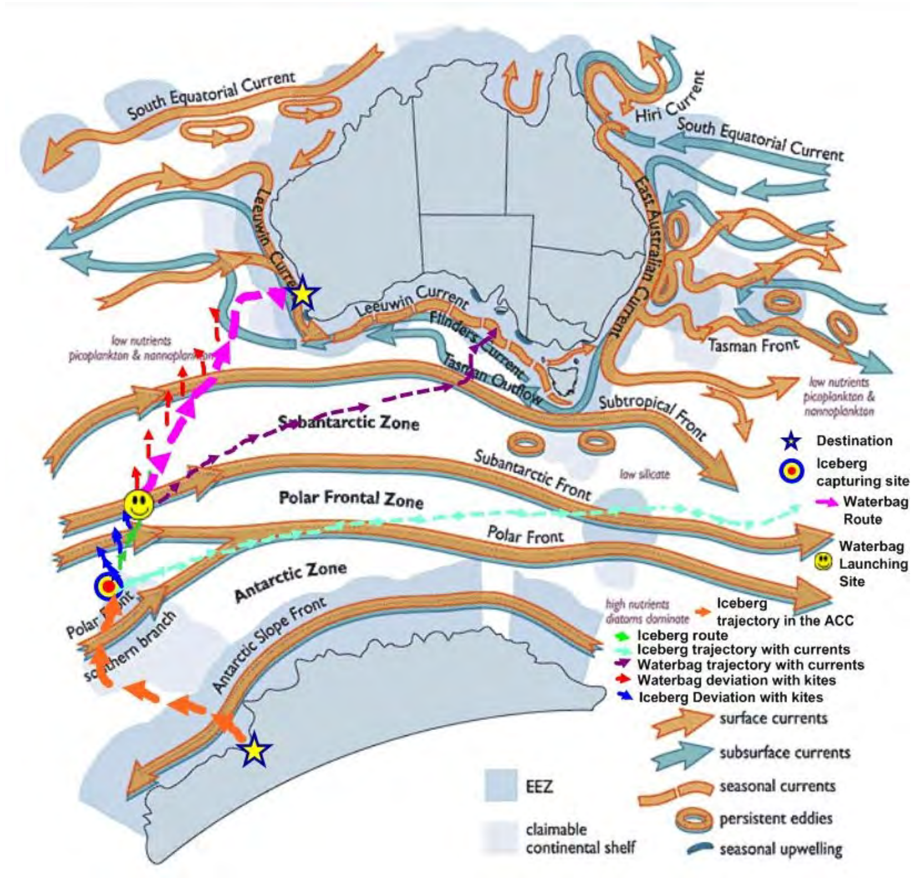

Figure 7.33 The Major Ocean Currents in the Australian Region (credit Edmonds, 2007[56] n.p.)

From Chapter 3 it can be seen that icebergs originated from the Amery Ice Shelf would drift through the currents of the Antarctic divergence to reach a region around the Kerguelen islands and Heard Island which corresponds to the iceberg capture zone for transportation projects to the AAT. Then icebergs would need to be carried over through the Antarctic Convergence with favourable current to be melted. Their water would be carried in the Antarctic Convergence currents to the AAT. Based upon calculations of the force of the most suitable currents and winds on the Amery shelf W route, a waterbag train could reach an average speed of 3.5 km/h tableau. The estimated speed for the propulsion generated by the Subantarctic current is 1 m/s (3.6 km/h) at the location of the Southern Ocean where the waterbags would be launched (Dhalluin, 1980). Up to 90% of the transport distance from the AAT to WA could be achieved based solely on the motive force of ocean currents. The directional effect of towing kites would enable trains of freshwater bags to pass from one current to another. Future experiments could assess the possibility of controlling the bag train with kites.

[56] www.waterengineeringaustralia.com.au/pdf/wea_0809.pdf

7.8.3 Kite-Assisted Control of Waterbag Direction

The aim of kite-assisted propulsion is to give direction to the waterbags. Kite-assisted propulsion takes advantage of the stronger winds that exist above the heights normally attainable by sails on masts (Breukels and Ockels, 2007; Breukels 2011[57]). Kiteship Corporation, a company specialising in the production of giant (up to 5,000 m^2) free-flying sail kites (Kiteship, 2010[58]), could manufacture a kite that could be connected to the waterbags via towing ropes, and managed by a fully automatic control pod. According to Spragg (2001), the main source of energy loss during towing is induced by the friction between the seawater and the bags. This loss increases as the train becomes longer. The dynamic interaction due to the wind and ocean current is greater at the front of the bag (Kiteship, 2007). The traction forces exerted by the kite would be transmitted to the convoy at the floating level. The force of the towing kite is transferred into the convoy's structure through a mechanism known as a deck lever arm that could link the kites to the convoy's structure (Figure 7.23b). Thus, the inclined position caused by the system is minimal and according to Skysails (2010[59] n.p.): "unlike conventional forms of wind propulsion, the heeling caused by the system is virtually negligible". At sea this system would reduce the effects of wave action and the uplifting force of the towing kite would allow the bags to 'cut' through the water. For the towing of a 100 m long waterbag with a kite, the maximum longitudinal stress on the attached string to the kite is 100 pounds/$inch^2$. It was previously reported that waterbag coating materials would enable the convoy to handle pressures in excess of 1,000 pounds/$inch^2$ in both longitudinal and transverse directions. Consequently for the transportation of a train of freshwater bags, several kites could be attached to several attachment points. A kite propelled by wind energy can improve the train displacement (Naaijen, Koster and Dallinga, 2006). The stern of the bag would have to distribute the upward component of the kite's force as the kite would exert its lifting and dragging force at this point. In order to be used for the transportation of the freshwater train the kites would need to have multiple attachment points so as to ensure uniform load distribution over the entire bag train. A stabilising net could be added to the skin of the bag to distribute the upward component of the kite's force throughout the bag. Kites attachment would have to be undertaken in order to provide uniform load distribution over the entire waterbag train. Such a system could be installed on a waterbag train. The forebags would be reinforced so as to withstand the extra pressure the towing force would exert on them. Towing kites would be

[57] http://repository.tudelft.nl/search/ir/?q='Breukels%2C+J
[58] http://www.kiteship.com/, http://www.kiteship.com/photoview.php?show=outleaderstudy.jpg
[59] http://www.skysails.info/english/products/the-skysails-technology/advantages-in-detail/

appropriate for waterbag transportation as they would be connected to the bags via a towing rope with a performance range; it would improve the safety of sailing operations. The objective of the kite system would be to provide a steady direction to the convoy. However, the towing kite could also be used to generate propulsion. As noted previously, the system could be adapted to iceberg waterbag transportation.

7.8.4 Sailing

Kites move according to equilibrium of the wind forces. It is possible to control kites velocities and directions by pulling on the control line and lifting the kites. Therefore flying performance can be calculated with mathematical models. According to Skysails (2010[60], p.3): "[T]he towing kite is aligned relative to wind direction, wind force, ship course and ship speed in order to achieve optimal propulsion power". The bag train could be controlled with the kites and appropriate controlling software as in the Skysails system. According to Skysails depending on the size of the system (2010, p.3): "the tractive forces are transmitted to the ship via a highly tear-proof synthetic rope". The ropes would connect the control pod to a force transmission point (tow point) at the bow of the bag and a winch with a transmission unit installed on the bag. The system conveys the kite's pull to the bag via towing ropes. The structure of the bag needs to be sufficiently dimensioned depending on kites and bags sizes. A comprehensive analysis of the stability is undertaken for each vessel before installing the kite system (Skysails, 2007). According to Brabeck (2010[61] p. 3): "[A] coupling mechanism connects the towing kite with the mast adapter attached to the launch and recovery mast." These kites can operate automatically. According to Skysails (2010, p.3): "[T]he steering system of the skysail propulsion operates automatically". According to Wintecc (Layman's report, 2006[62] p.8):

> The launch and recovery system manages the deployment and lowering of the towing kite. It is installed on the forecastle and consists of a telescopic mast with reefing system that unfurls and reefs the kite during the launch and recovery process... Force transmission point, launch and recovery system as well as the kite storage are all included.

According to Skysails (2010 p. 7):

[60] http://www.skysails.info/english/products/the-skysails-technology/advantages-in-detail
http://www.skysails.info/fileadmin/user_upload/documents/Dokumente/SKS_Broschueren/EN/EN_Technology_Information.pdf
[61] http://www.e-fishing.eu/paperslist/papers/17SkySails-New_Energy_for_Fishing_Trawlers.pdf
[62] http://www.wintecc.de/fileadmin/user_upload/_temp_/20100609-Layman-Report-en.pdf

> The recovery process is performed in the reverse order of the launch. The winch retracts the towing rope and the towing kite docks on the launch and recovery mast. The towing kite is then reefed. The telescopic mast retracts and the towing kite is stowed in the kite storage along with the control pod. The entire launch and recovery procedure is carried out largely automatically and lasts approx. 10-20 mins each.

However, the stowing kite can be used on courses up to 50° close to the wind due to the aerofoil profile as opposed to that of a spinnaker (Skysails, 2007). According to Skysails (2007) in practice from 70° onwards high propulsion can be achieved, while the most efficient courses are between 120° and 140°. Kite functioning would be automated and could provide a reliable means of controlling the direction of the waterbag train. During the sailing, kites are driven by an autopilot unit. One computer helps the kite to maximise the power the other adjusts the kite's direction (Skysails, 2010). According to Skysails (2010 p. 10): "[I]f the airflow velocity is doubled, the tractive force of the Skysails System quadruples. In practice, the towing kite can easily reach speeds three times that of the present true wind". The crew should be trained to learn the fundamentals of kite towing technologies.

7.8.5 Propulsion System

As noted by O'Rourke (2006) the main advantage derived from a kite propulsion system is the reduction of the fuel consumption, as illustrated in Figure 7.34.

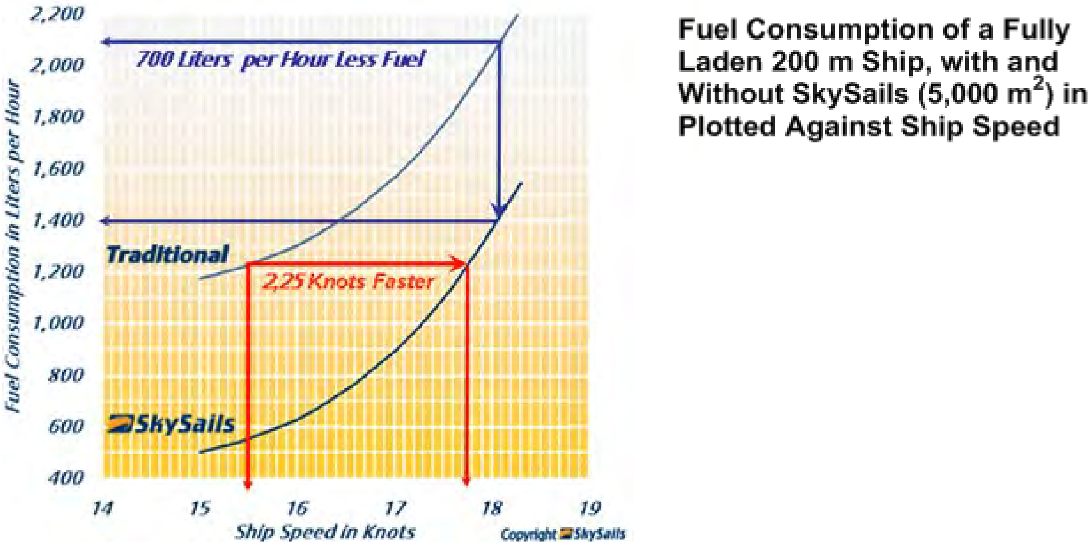

Figure 7.34 Fuel Reduction with a 5,000 m² kite for a 200 m Ship (credit Skysails, n.d.[63] CRS - p. 25)

[63]http://www.ibiblio.org/hyperwar/NHC/CRS/propulsion.htm

A fully laden 200 m ship equipped with 5000 m² Skysails reduces the fuel consumption by 700 l/h and increases the speed by 2.25 knots, compared with a traditional ship. Pulling a large tabular iceberg (100 million t, 4 km x 500 m x 500 m) at 1.6 km/h generates a power requirement of 200,000 kW. It is estimated that 2,200 kW are needed to tow an iceberg of 1 million t at a speed of 1.5 km/h (0.5 m/s) and only 800 kW for an equivalent volume of melted water stored in a bag (Sobinger, 1985). Waterbags are adapted for marine transportation, so their drag resistance is at least 10 times less than the resistance of an iceberg (Sobinger, 1985). This means that less propulsion force is required to transport them or to give them direction. With a bollard pull of 110,000 pounds it is possible to pull a string of fifty bags, weighing 1,300,000 t, at a speed of 4 km/h (Spragg, 2001). Table 7.2 gives the relations between the Kites surface and the power needs for iceberg transportation projects. We saw earlier that Skysails currently proposes 5,000 kW kites (Chapter 6).

Table 7.2 Relations between Kites Properties and the Power Needs for Iceberg Transportation

			Force Pounds	**Force GW**	**Effective pull**	**Kite surface**
10^8 t iceberg	Speed 2 km/h	Towing	5,000,000	200	4,000	100,000
		Steering	2,000,000	80	1600	20,000
		Bags	2,000,000	80	1600	20,000
	Speed 0.7 km/h	Towing	1,000,000	40	800	10,000
		Steering	400,000	16	320	4,000
		Bags	400,000	16	320	4,000
2.5 10^7 iceberg	Speed 2 km/h	Towing	1,250,000	50	1000	12,500
		Steering	500,000	20	400	5,000
		Bags	500,000	20	400	5,000
	Speed 0.7 km/h	Towing	250,000	10	200	2,500
		Steering	100,000	4	80	1,000
		Bags	100,000	4	80	1,000
8 10^6 t iceberg	Speed 2 km/h	Towing	400,000	16	320	4,000
		Steering	160,000	6.4	128	1,600
		Bags	160,000	6.4	128	1,600
	Speed 0.7 km/h	Towing	80,000	3.2	64	00
		Steering	32,000	1.28	25.6	320
		Bags	32,000	1.28	25.6	320
1 10^6 t iceberg	Speed 2 km/h	Towing	50,000	2	40	500
		Steering	20,000	0.8	16	200
		Bags	20,000	0.8	16	200
	Speed 0.7 km/h	Towing	10,000	0.4	8	100
		Steering	4,000	0.16	3.2	40
		Bags	4,000	0.16	3.2	40

As the strongest waterbag material is able to sustain 1,000 pounds/inch, theoretically 40 attachment points on a one million t train would be able to transmit the pull of the giant kites effectively. Three very large kite systems (20,000 m²) could pull a bagged iceberg at average speeds of around 1 km/h. The kite system attached to the icebergs would have a much weaker effect than attached to a waterbag train. Depending on their characteristics with optimisation of waterbag size, shape, resistance and hydrodynamic features and an optimal use of currents and kites the bags could increase the efficiency of the kite pull, which could provide up to 14 km/h (4 m/s). The critical means of adapting the existing kite system to the requirements of the proposal outlined in this chapter are both for waterbag transportation and for iceberg bag transportation to create a specific installation built in both the waterbag and the megabag structures which could transmit the tractive force of the kite to the waterbag. A specific leader bag with reinforcements and a semi rigid structure could be designed to receive and transmits the main propulsion from the kites. The currents of the Southern Ocean from the Kerguelen Island to WA coasts are particularly favourable, in terms of direction as strength (Smith and Banke, 1983[64] see also Table 7.1 Figure 7.35).

[64]http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V86-488G7Y6-2B&_user=10&_coverDate=02%2F28%2F1983&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1585283337&_rerunOrigin=google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=28a8ea35129e35a7ecc0d7171d32484c&searchtype=a

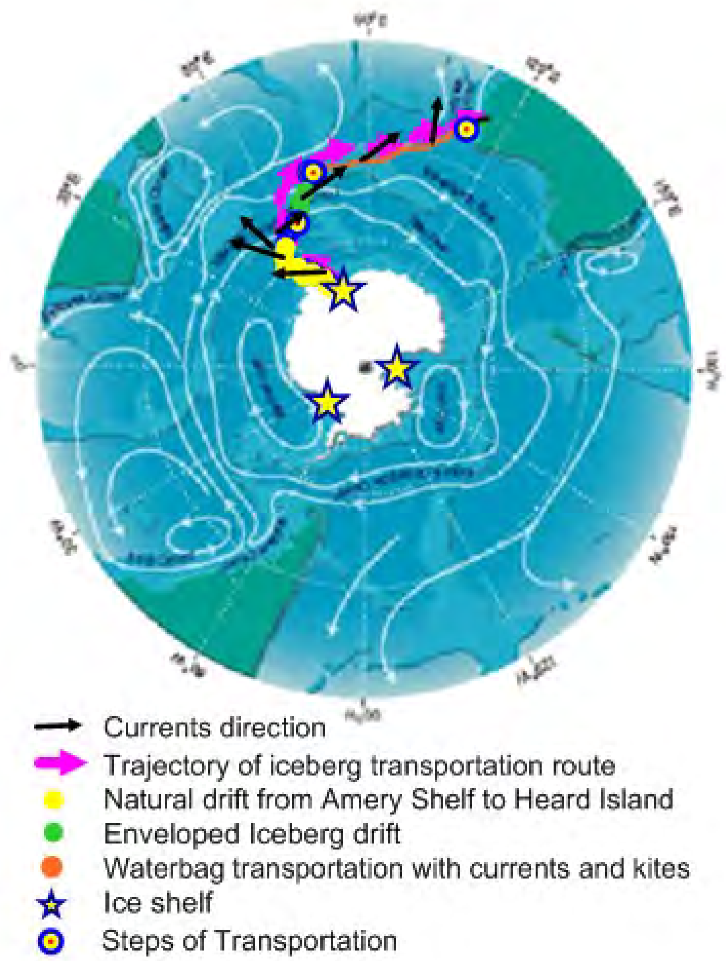

Figure 7.35 Schematic Map of Major Currents in the Southern Hemisphere (credit from Pearson Prentice Hall, 2004[65] n.p.)

The yearly average wind speed is 100 km/h in Kerguelen Island (Dunn, 2010[66]). Up to 90% of the conveying distance from the AAT to WA would be covered by ocean currents with the use of the towing kites to secure the directions of the bags and to pass from one current to another. In optimal conditions, the route between the Kerguelen Island and WA could be covered in less than a month. The combined action of maritime currents and the wind could develop an average velocity of 2 to 4 m/s for the displacement of the train of bags.

7.8.6 Sensors

Radar sensors monitored by satellites, could be used for surveying and locating the waterbags as they undertake their slow journey drifting on the ocean currents. Equipping

[65] http://www.divediscover.whoi.edu/ecosystem/circulation-en.html
[66] http://www.greenerideal.com/science/8504-earths-pristine-places-kerguelen-island

waterbags with individual sensors could minimise the risk of collision between waterbags and other floating objects by using C-CORE icebergs detection practices (C-CORE, 2005).

7.8.7 Route Planning, Itineraries, Meteorological Conditions

Multi-discipline data such as "iceberg position, profile, wind and current monitoring, drift trajectory forecast" (PERD report 20-84, 2007, p. 70) are necessary to coordinate iceberg and freshwater train planning routes. From the Ronne Ice Shelf or the Amery shelf to WA, the winds and currents are favourable for iceberg and freshwater transportation. For a 25 million t iceberg, the 3,300 km journey from the Amery Ice shelf in the AAT to Perth, WA would be complete first by the natural drift of the iceberg on 1,400 km, then by the transportation of the bagged iceberg on 600 km at a speed of 1 km/h; then the iceberg transportation techniques outlined above, using kites and currents, would allow the transportation of the waterbags on 1,400 km at a speed of 6 km/h and then the waterbags would be delivered to Freemantle on the last 300 km at a speed of 14 km/h. The journey (and the melting) would take from the day of capture to the delivery from two to four months (depending on weather conditions and related melting rates and sailing conditions). The optimal operational conditions for both melting and transporting the iceberg occur during the Antarctic summer. To melt, the iceberg needs solar energy and warm water temperatures of the Antarctic summer. During iceberg break-up from the Amery shelf and freeze-up after breaking, sailing conditions are particularly dangerous, with wind speeds of up to force 9. The pre-melting operations, such as iceberg detection, selection, towing, harnessing and wrapping, and transportation to a warmer zone, would ideally be achieved during spring. The iceberg would be wrapped in early September, melt and drift from October to February up to 50° S and be transported from mid February to July. Meteorological and oceanic data would be used to plan the most appropriate route for the waterbag train. The kite system could be used to optimise the route. According to Brabeck (2010 p. 3): "[T]he predicted optimal route [is] translated into a series of waypoints... facilitates the utilisation of the most advantageous winds". According to Skysails (2010 p. 9) "the potential routes and speeds are then calculated". The waterbag train could be guided to its destination using the most efficient currents and winds. During freshwater transportation the course of the convoy would be optimised by specific routing software, which defines the route by incorporating the latest local weather forecasts. According to Skysails (2010 [67] n.p.): "[M]odern meteorological methods make precise three to five-day weather forecasting possible. Major weather

[67] http://www.skysails.info/english/products/the-skysails-technology/operation-safety/

systems and weather trends can be forecast for even longer periods". The waterbags convoy would reach calmer seas, around 45° S, in around two months. A timetable of processes from iceberg selection to ultimate freshwater delivery is presented in Table 7.3.

Table 7.3 New Technological Approaches for Icebergs Water Transportation from the AAT to WA

Step	Operations	Description	Time
1	Iceberg selection and modelling	An 'ideal' iceberg (tabular, elliptical in section and free of cracks) is detected and selected. Determining the iceberg's physical properties (geometry of a variable volume, gravity centre, axis)	Several days
2	Sensing of gravity centre of iceberg and cracking risks	Safety reasons for humans and equipment. Melting sensing	Continuous
3	First logistical installation over iceberg	Auto supporting structure composed of the winch, materials and the structure for humans, maintenance, equipment and storage. Peripheral belting	Several days
4	Iceberg's wrapping with an internal filet	Insertion of metallic net and protective structure against mechanical destructive waves' action, degradation, cracking, with a filet enhancing iceberg's stability	Several days
5	Iceberg wrapping	Auto supporting. The selected iceberg is enclosed into the megabag	Several days
6	Collar attachment to the megabag. Empty waterbags connexion to the collar	Melted water storage, and iceberg stabiliser	Several days
7	Iceberg towing in a safety region	Harnessing and slowly transporting the iceberg in warmer waters with kites	Several weeks
8	Iceberg melting freshwater collection a collar	Melted water collection into the iceberg bag collar, device for melting acceleration melt techniques	Several months
9	Fill-up of the waterbags	Fill-up the water bags with fresh melted water	Several months
10	Detaching	Detaching waterbags stored in special parking and transported to the connexion stands	Less than 24h/waterbag
11	The links of train of waterbags	Disconnecting of the waterbags from the collar. The train would be composed of 20 rows of three links of bags.	2 days
12	Launching	Launching the waterbags or the waterbag train into the currents	1 day
13	Sustainable train transportation with currents	Itineraries, for currents, winds optimisation	Several weeks
14	Delivery	Catching the waterbags or the waterbag train and delivery.	Several days
15	Tests related to water quality and sanitary control of bags	Water quality control would be performed by the WA sanitary authorities in agreement with Australian norms for water	Several days
16	Cleaning and preparing the bags for the next voyage	Sanitary certificates are needed for each waterbag before undertaking the next voyage	Several days

The estimation of the principal elements for the transportation of a 1 million m^3 freshwater from a melted Iceberg are given in Table 7.4.

Table 7.4 Estimation of the Principal Elements for the Transportation System of a 1 million m^3 Iceberg

Elements for a 1 million m^3 iceberg	Size for a 200 m by 100 m by 50 m iceberg
Foam	600 m by 50 m by 1 m = 3,000 m^3
Collar	600 m by 50 m by 30 m 100,000 m^3 expandable up to 600 m by 50 m by 300 m for 1,000,000 m^3
Mega bag capacity	100,000,000 m^3
Net capacity	1,000 000,000 m^3
Fresh waterbags	15 bags/sector x 8 sectors = 120 waterbags of 17,000 m^3 and 1 bag is 100 m long by 14 m diameter
Kites sail area	50 m by 10 m = 500 m^2

This system is flexible and can be adapted to different requirements ranging from experimental scales to large *in situ* real-size scales.

7.8.8 Risks

During iceberg transportation, the most important risks are collision with other icebergs or vessels and iceberg splitting. These latter risks can be partially prevented using a netting technique to secure their stability, a megabag in which the iceberg is encapsulated during transportation and a collar to protect against continuous wave erosion(Sobinger, 1986; Hewlings, 1989; Fuerle, 2003; Abramovitch, 2004; C-CORE, 2005[68]). The equilibrium of the iceberg, the melted water and the volume of the air encapsulated into the megabag plays an important role in megabag stability. The melted water contained in the megabag could help to reduce the risk, by accelerating and homogenising iceberg melting, thereby reducing the likelihood of the iceberg ‘turning turtle’ (capsizing).

Concerning the waterbag the main risk would be the potential breakage of a megabag and the potential collision of the bag. For the collision issues, an assisting vessel could be in charge to accompany the convoy, help it to detect any potential problem and assist it in case of emergency or unexpected issue. For the potential breakage, minimising slamming and torsion forces would increase the safety of the operations and extend the life of the waterbags. In the event that the waterbags are lost, the material of the bags and the kites are environmental friendly. According to Brabeck (2010 n.p.): “[T]he towing kite and rope as

[68]http://www.nrc-cnrc.gc.ca/eng/ibp/chc/reports/ice-engineering.html

well as the control pod are light and would float on the water after being released… Towing kites and towing ropes are relatively cheap wearing parts." According to Skysails, (2010) "[A] multi-level security system and redundant components guarantee the highest possible safety during operation of the Skysails propulsion."

Further multi-disciplinary research, including tank trial experiments, is needed to develop both bagged iceberg and waterbag transportation technology, including safety aspects. The parameters to be taken into consideration could include: currents, waves, winds, ice, bathymetry and the Earths rotational parameters such as the Coriolis force and the Polflucht force (Kraft and Bauer, 1998[69]).

7.9 Freshwater Delivery

The freshwater bag train would drift close to its final destination, around 100 km away from WA coasts. At this point a tug boat would secure the delivery of the train to Freemantle Harbour. Specific infrastructure is needed to deliver freshwater from the waterbags floating on the ocean to a shore storage facility. Several companies have developed structures for freshwater delivery. According to Spragg (2004 n.p.) infrastructures developed included:

> [S]hore side facilities to handle water from the source (pump stations, water storage structures) ocean pipelines to offshore water-loading platforms, bag assembly facilities to prepare and deliver empty bags to the water-loading facility, and off-loading facilities to remove water from the bags.

The freshwater bags could be removed from the sea water and emptied, by rolling onto a frame winched round a giant spool. The empty bags could then be loaded by support onto a barge in preparation for their reuse (Edmonds, 2006; Sobinger, 1985). Water filtration facilities, pumping systems, pipelines and reservoirs are needed. Most of these facilities have already been built and used successfully in different harbours all over the world. The water from the waterbags could be pumped directly in the different types of freshwater systems (pipes, channels, dams, underground storages). Water quality tests would have to be undertaken.

[69] https://authors.aps.org/eprint/files/1998/Mar/aps1998mar04_001/main.revtex

As an example CH2M-Hill designed for Spragg company a water delivery system requiring the following major components (Spragg, 2004[70] n.p.):

1. shore side facilities to handle water from the source (i.e., pump stations, water storage structures.) and ocean pipelines to the offshore water-loading platforms;
2. water-loading platforms to fill the bags;
3. bag assembly facility to prepare and deliver empty bags to the water-loading facility. [Bags would be made from recyclable environmentally friendly materials];
4. off-loading facility to remove water from the bags; [The freshwater bags are removed from the sea water and emptied, by rolling onto a frame winched round a giant spool then loaded by gantry onto a barge. The skin of the bags would be made from special layered composite materials];
5. transport system to tow full bags to a marshalling facility;
6. marshalling facility to assemble bags into towing strings for transport to delivery sites;
7. empty bag handling and transport system to rig empty bags for the return trip to the loading facility;
8. mooring and bag handling facilities in the vicinity of the off-loading facility;
9. ancillary facilities, such as water filtration plants, booster-pump stations, pipelines to municipal reservoirs or wells, and ocean pipelines from the off-loading facilities.

7.10 Conclusion

This chapter proposes an original technology for iceberg transportation and freshwater transportation and delivery from the AAT to WA. From previous studies published between

[70] http://www.waterbag.com/history/history.htm

1970 and 2005, three main unsolved problems are apparent: ensuring iceberg stability during transportation; the high cost of fossil fuel used in transporting the icebergs and fresh water; and the need to employ environmentally friendly material and technologies;

To solve these problems, my original contribution is to split the process of iceberg melted freshwater transportation from the AAT to WA into two distinct parts:

- the melted fresh water would be collected first in a megabag and then transferred into a collar, which is a flexible, attached temporary offshore base,
- the freshwater would be transported in waterbags to a selected destination in WA, propelled by kites and Southern Ocean currents.

The proposed new system includes specific processes to capture and wrap the iceberg in a 'megabag', an attached offshore flexible temporary collar collecting system that both collects iceberg melted freshwater and stabilises the iceberg during melting and a new type of oceanic waterbag for freshwater transportation, assembled in a train propelled by kites and maritime currents. The main iceberg freshwater transportation technological aspects are:

1. selection of a suitable iceberg;
2. capturing the iceberg;
3. wrapping the iceberg;
4. protecting the iceberg with an internal net;
5. netting the iceberg with an external net;
6. putting a collar around the melting iceberg;
7. iceberg towing in a safety region, deploying collar and melting;
8. collecting melted water in the waterbags;
9. assembling together a number of freshwater bags to form a train;
10. launching the freshwater bags into the sea water or launching the train into the current;
11. launching the kites;
12. sailing the train of bags with natural forces, currents and wind;
13. surveying the bag train during sailing;
14. delivering the freshwater bags at destination;
15. recovering the iceberg bag, collar, net and structure;
16. carrying out tests related water quality and sanitary control of bags;
17. preparing the iceberg bag and collar for the next use;
18. cleaning and preparing the waterbags for the next voyage or for other uses.

Although data are limited they are adequate to evaluate the preliminary feasibility of the technical elements of iceberg transportation selected in this thesis. They are able to answer most of the transportation issues raised by previous iceberg transportation projects, even at very large scales. Transporting a bagged iceberg in a megabag with nets to stabilise it during the melting process would partly solve the stability problem whereas transporting the waterbags with currents and kites would partly solve the issue related to fuel consumption. Information concerning operating conditions for both the bagged iceberg transportation and the waterbags ocean transportation were given. In the next chapter sustainability issues will be studied as well as technologies to reduce potential environmental impacts.

Chapter 8 Environmental Impacts of Iceberg Transportation

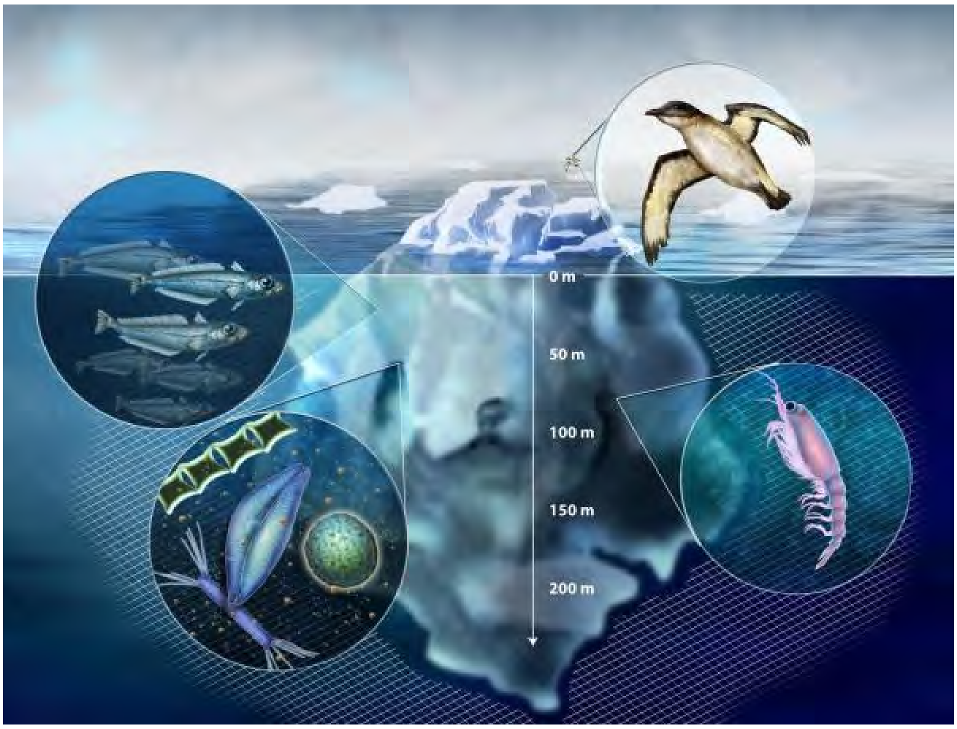

Figure 8.0 Icebergs Hold Trapped Terrestrial Material, Which they Release Far Out at Sea as they Melt (credit Rager Fuller, NSF, 2007[1] n.p.)

Some scientific results depend only on
lucky conditions and good application with which
the mind makes use of.
(Translated from Weil, 1935 p. 17)

[1] http://www.nsf.gov/news/news_summ.jsp?cntn_id=109653

Chapter 8 Environmental Impacts of Iceberg Transportation

The objective of this chapter is to examine and evaluate the types of environmental impacts associated with an iceberg transportation system. Responding to a request from the Australian Government to evaluate the likely environmental effects that might result from the actual process of transporting an iceberg, the AAD conducted an initial analysis (Schwerdtferger, 1986). This analysis concluded that the environmental effects that might arise during transit were minimal. Interviewed in the early 2000s, Quilty (2001b) confirmed that iceberg harvesting using traditional techniques of transportation described in the projects of the 1970s would have minimal impact on the Antarctic environment. However, these analyses require updating and more detailed study on potential impacts of iceberg transportation which are only possible once a transportation system is selected. The transportation system introduced in Chapter 7 of this thesis was designed taking into consideration the environmental analysis of this chapter in an interactive way. This chapter will provide more in-depth elements for an environmental impact assessment for a preliminary iceberg transportation project based on the transportation system identified in Chapter 7. First the types of environmental impacts likely to result from iceberg transportation will be introduced. There are a number of potential environmental impacts that would also arise at the waterbag processing site, and these impacts are discussed and options for mitigation outlined. Traditional iceberg transportation systems have relied heavily on fossil fuels as the energy source for transportation. These systems are not only costly to run because of the price of the fuel; the associated pollutants given off by combustion constitute a negative externality which adds up to the global cost by adding an indirect cost to be paid by societies globally or regionally. One significant means of reducing the environmental burden of iceberg freshwater transportation system would consist in reducing these emissions and using technologies less reliant on fossil fuels. Finally, the chapter concludes with an assessment of whether these associated environmental impacts are significant or not and what that means for the proposal, outlined in the previous chapter, to transport icebergs from the AAT to Perth in West Australia.

8.1 Background

In 1987 the Brundtland Commission defined sustainable development as the capacity of the global economy to "meet the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987 n.p.[2]). "All form of assets (capital, real estate, infrastructures, resources) passed on to the next generation should be at least of equal value (utility) per capita" (Rodrigue and Comtois, 2009[3] n.p.). Within the transportation sector, the implementation of strategies to increase sustainability relies on working with the present spatial organisation and the distribution of transport networks in order to create technological conditions which can allow a reduction in environmental damage, and result in higher cost-effective levels of integration and increasing levels of accessibility. Transportation "supports the interactions and the development of socioeconomic systems" (Rodrigue and Comtois, 2009[4] n.p.). Transportation is sustainable when social equity conditions, satisfying the diversified needs of the population, are favouring the accessibility to resources for present and future generations. However, transportation systems generate wastes (vehicles, parts, emissions and packaging) that must be reduced. Transportation systems are often based on technologies that consume hydrocarbons (Rodrigue 2009). Maritime trade has multiplied by three since the 1970s. In 2006 it reached over 7 billion t of freight (UNCTAD, 2007). Transportation activities are causing gradually more environmental problems (OECD, 1988). "The relationships between transport and the environment are multidimensional" (Rodrigue and Comtois, 2009[5] n.p.). In a context characterised by global growth in the production of polluting emissions, transport systems need to improve their flexibility and adaptability to face the challenges of protecting the environment. According to Rodrigue and Comtois (2009[6] n.p.): "[T]he main factors considered in the physical environment are geographical location, climate, atmosphere, hydrology, topography, geological structure, soil, natural vegetation and animal life."

Air pollution is a common source of environmental externalities for transportation linked to consumption levels. There is a current debate about the range of impacts greenhouse gas emissions may have on climate change. Transportation activities generate annually millions of tons of CO_2 emissions (Rodrigue, 2009). These sources of pollution affect air quality and cause damage to human health (Holmen and Niemeier, 2003).

The first source of environmental impacts on the hydrosphere is caused by transportation pollution. Transportation accounts for up to 25% of all nitrogen fallout in the form of water, sulphuric and nitric acids (Rodrigue, 2009).

[2] http://www.un-documents.net/wced-ocf.htm
[3] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/ch8c4en.html
[4] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/ch8c4en.html
[5] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/ch8c1en.html
[6] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/ch8c1en.html

Water pollutants emitted by transport systems can cause damage to forests, such as reduced photosynthesis, and lead to the acidification of soils and the accumulation of poison in the aquatic food chain of marine ecosystems. According to Rodrigue and Comtois, (2009[7] n.p.): "[B]ecause demand for shipping services is increasing, marine transport emissions represent the most important segment of water quality inventory of the transportation sector."

Maritime transportation generates several major impacts from waste, ballast waters, oil spills, infrastructure impacts, de-icing, runoffs and hazmats. Different sorts of wastes are not easily biodegradable. Oil spills from vessel accidents generate pollution that can destroy maritime ecosystems (Talley, 2003) Economic, social and environmental costs occur. The arrival of new invasive species have transformed coastal ecosystems such as lagoons and inlets (Leppäkoski *et al.*, 2002a, 2002b; Gollasch and Panov, 2006).

Transportation systems and their related infrastructure affect hydric systems (Rodrigue 2009). Construction and maintenance of maritime transport infrastructure, particularly harbours, piers, terminals and waterways, can cause disruption to a hydrological environment like a river, wetland or a coastal area. Natural habitat removal, and modification of the aquatic environment are some of the effects of establishing maritime transportation infrastructure. Coastal infrastructures and maritime transportation modify interaction with the impact of waves, fetch, and coastline shapes. The construction of operating infrastructure and vessels are high energy consuming activities (Rodrigue and Comtois, 2009).

De-icing of infrastructure disrupts ecosystems and can kill micro organisms. De-icing salts are released in the hydrographic system and can interfere with plant growth and aquatic life reproduction cycles.

8.2 Environmental Impacts of Iceberg Transportation

Any activity involving the removal of resources from Antarctica should comply with the Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol). The Madrid Protocol requires that activities within the Antarctic Treaty must have an environmental impact

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[7] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/ch8c1en.html

assessment. The ATCM XXVIII in Resolution 4 (2005[8] n.p.) provides EIA Guidelines. The standard categories of impacts used in the EIA system are:

- less than minor or transitory;
- equal to minor or transitory;
- greater than minor or transitory.

Any activity determined as likely to have a minor or transitory impact should be evaluated with an Initial Environmental Evaluation (IEE). In the Protocol the highest level of assessment corresponds to the procedure described in Article 8 as the Comprehensive Environmental Evaluation which is prepared for activities likely to have more than a minor or transitory impact. The guidelines for CEEs can therefore provide us with a suitable technical framework to discuss the environmental impacts of iceberg transportation. A CEE should include (COMNAP 1999, Fallon and Kriwoken 2005[9] p. 78, AAD 2010[10]):

a. non-technical summary;
b. description of the proposed activity;
c. description of the existing environment;
d. description of methods and data used to predict impacts;
e. analysis of expected impacts;
f. alternatives;
g. mitigation measures;
h. monitoring of impacts;
i. conclusion;
j. contact name and address; and
k. external consultation and proponent response.
l. response action in case of accident;
m. audit arrangements.

[8] http://www.ats.aq/devAS/info_measures_listitem.aspx?lang=e&id=349, http://www.ats.aq/documents/recatt/att266_e.pdf
[9] http://eprints.utas.edu.au/2995/1/Environmental_Impact_Assessment_Antarctic_Treaty.pdf
[10] http://www.antarctica.gov.au/protecting-the-environment/environmental-impact-assessment-approvals-and-permits/environmental-impact-assessment/environmental-impact-assessment-iee-and-cee

Steps a, b and c dealing with a non-technical summary of the activity, the description of the proposed activity and the description of the existing environment were covered in Chapters 1, 7 and 3 of this thesis and steps d and h concerning the description of methods and data used to predict impacts and the monitoring of impacts should be left for future investigations. This chapter will focus on steps d, e, f, g and i regarding the analysis of expected impacts, the alternatives, the mitigation measures and the response action in case of accident.

8.3 Level of Exposure of Iceberg Environment

Icebergs are a fundamental element of polar environments and as such icebergs need to be considered as environmental resources. Icebergs as water resources have specific supplying yields. However, because of global warming it is difficult to assess the environmental impact of any iceberg transportation system as any impacts will likely be 'masked' by the impacts of global warming. The level of impacts of iceberg utilisation on iceberg environments depends on their yield and melting rates and in case of operating them on their operating rates (in terms of water production). These operating rates would have to be put in perspective with their yielding and melting rates (Ryland, 1997). An intense iceberg utilisation could stress significantly the ecosystems located around icebergs. The potential for a local over-use exists. Conditioning the operating volumes to the principle of sustained yields and scales would ensure that there would not be any depletion of the resource:

- the annual volume of icebergs produced is estimated to be between about 800 and 1,200 km^3/yr (Hult and Ostrander, 1973);
- the annual volume of iceberg melting is estimated to be between 200 and 300 km^3/yr (Hult and Ostrander, 1973);
- the annual volume of iceberg drifting in the Southern Ocean is estimated to be between 4,000 and 7,000 km^3/yr (Hult and Ostrander, 1973[11]) depending on exceptional events (for instance in case of a major break-up and other large calving) and iceberg production rhythms. Accelerated rates of ice shelve sliding has resulted in more icebergs being produced over the last decades (Oppenheimer and Alley, 2004);
- the world's consumption of freshwater is around (5,000 km^3);
- an annual operating rate is commonly set between 10% and 30% of the low estimates of renewable water resources in order to ensure minimal environmental impact levels and an appropriate rate of renewability.

[11] http://www.rand.org/pubs/reports/2008/R1255.pdf

Icebergs can interact in the following ways on polar ecosystems:

- optical: icebergs can block sunlight from reaching the ocean floor (Heizer, 1978);
- physical: scouring and drifting can induce the displacement of individuals and disturb marine populations. Collisions can occur;
- thermal: thermal cooling from icebergs occur and condensation increases fogging;
- chemical: mineral exchanges (the iron elements contained in icebergs are used by plankton blooms) and local saline pollution with decreases in salinity and freezing occurs;
- biological: indigenous species contained in iced water and released by the input of this water can modify the composition of benthic communities or zoo and phytoplankton communities. Algal and planktonic populations ultimately reside in the melted water (Goldman, 1979). Wildlife interacts directly with icebergs as a habitat (Goldman, 1979). The impacts of icebergs naturally drifting in the Southern Ocean on pelagic ecosystems is not well documented (Smith *et al.*, 2007). However icebergs affect ecosystems as their impacts can ultimately increase and decrease biological activities. The IUCN, the International Union for Conservation of Nature, defined a list of endangered species in the Southern Ocean corresponding approximately to the selected operating zone identified in Chapter 7 (Table 8.1).

Table 8.1 IUCN List of Endangered Species in the Southern Ocean (credit IUCN, 1994[12] n.p.)

Scientific Name	**English Name**	**IUCN Category**
	Whales	
Cephalorhynchus commersonii	Commersons dolphin	Data Deficient
Lagenorhynchus obscurus	Dusky dolphin	
Berardius arnuxii	Arnoux's beaked whale	Least Concern
Phocoena dioptrica	Spectacled porpoise	Data Deficient
Balaenoptera musculus	Blue whale	Endangered
Ziphius cavirostris	Cuvier's beaked whale	Data Deficient
Mesoplodon grayi	Gray's beaked whale	Data Deficient
Mesoplodon hectori	Hector's beaked whale	Data Deficient
Megaptera novaeangliae	Humpback whale	Vulnerable
Globicephala melas	Long-finned pilot whale	Least Concern
Caperea marginata	Pygmy right whale	Least Concern
Balaenoptera borealis	Sei whale	Endangered
Hyperoodon planifrons	Southern bottlenose whale	Least Concern

12 www.redlist.org

Eubalaena australis	Southern right whale	Least Concern
Physeter macrocephalus	Sperm whale	Vulnerable
Seals		
Arctocephalus gazella	Antarctic Fur Seal	Least Concern
Arctocéphale De Kerguelen	Kerguelen Fur Seal	
Mirounga leonina	South Atlantic elephant seal	Least Concern
Birds		
Thalassarche melanophrys	Black-browed albatross	Endangered
Thalassarche chrysostoma	Grey-headed Albatross	Vulnerable
Phoebetria palpebrata	Light-mantled Albatross	Near Threatened
Phoebetria fusca	Sooty Albatross	Endangered
Diomedea exulans	Wandering Albatross	Vulnerable
Larus dominicanus	Kelp Gull	Least Concern
Pelecanoides urinatrix	Common Diving-petrel	Least Concern
Pelecanoides georgicus	South Georgia Diving-petrel	Least Concern
Halobaena caerulea	Blue Petrel	Least Concern
Daption capense	Cape Petrel	Least Concern
Pterodroma macroptera	Great-winged Petrel	Least Concern
Procellaria cinerea	Grey Petrel	Near Threatened
Lugensa brevirostris	Kerguelen Petrel	Least Concern
Macronectes giganteus	Southern giant petrel	Vulnerable
Oceanites oceanicus	Wilson's Storm-petrel	Least Concern
Procellaria aequinoctialis	White-chinned petrel	Vulnerable
Pterodroma lessonii	White-headed Petrel	Least Concern
Fregetta tropica	Black-bellied Storm-petrel	Least Concern
Garrodia nereis	Grey-backed Storm-petrel	Least Concern
Pygoscelis papua	Gentoo penguin	Least Concern
Aptenodytes patagonicus	King penguin	Least Concern
Eudyptes chrysolophus	Macaroni penguin	Vulnerable
Eudyptes chrysocome	Rockhopper penguin	Vulnerable
Anas eatoni	Eaton's Pintail	Vulnerable
Pachyptila desolata	Antarctic Prion	Least Concern
Pachyptila belcheri	Slender-billed Prion	Least Concern
Phalacrocorax aristotelis	European Shag	Least Concern
Chionis minor	Black-faced Sheathbill	Least Concern
Catharacta skua	Great Skua	Least Concern
Sterna vittata	Antarctic Tern	Least Concern
Sterna virgata	Kerguelen Tern	Near Threatened
Fish		
Bathyraja eatonii	Eaton's Skate	Data Deficient
Bathyraja irrasa	Kerguelen Sandpaper Skate	Near Threatened

Seabird populations, marine mammals, fish populations and planktonic communities are the most sensitive elements of the ecosystems which could be affected by iceberg transportation (Goldman, 1979). The Antarctic ecosystem is very fragile and experiences significant spatial and temporal variations, particularly at higher latitudes: zooplankton species located with a Circumpolar distribution (Atkinson et al. 2008, KRILLBASE, 2010; See also Appendix 3) are the main food sources of Antarctic fur seals and chinstrap penguins or macaroni penguins, which dominate (Hofmann *et al.*, 2004). More specifically the Antarctic Peninsula biological community appears to react strongly to environmental changes: Krill larvae are sensitive to food and temperature conditions and are sheltered by winter sea ice where they rise from the bottom of the shelf of oceanic areas (under 2,000 m depths) to 60 m depths where they bloom (Marr, 1962; Lochte, 2009). Krill reach maturity after two years and continue their life cycle until six years. The Antarctic Peninsula krill stocks decreased over the past 25 years (Atkinson *et al.*, 2008; Lochte, 2009). Consequence of warming could be a modification of the ecosystem structure with influx of crabs (McClintock *et al.*, 2008). The loss of these nutrients combined with the loss of sea ice also affects Adélie penguin population which decreased in the Ross Sea by two third in the past 30 years (McClintock *et al.*, 2008). In the Southern Ocean salps dominate benthic invertebrates such as sponges and corals in oceanic regions with lower food concentrations. Higher trophic level predators such as Chinstrap and Gentoo penguins, seals, whales, and sea birds prefer also these warmer waters of pack-ice-free regions (Lochte, 2009). Very little is known on their sensitivity to the types of disturbance induced by iceberg transportation operations partly because the levels of disturbance of iceberg transportation activities are as yet unstudied. Concerning an iceberg transportation environmental protocol relevance, capturing and transportation operation should be restrained to specific zones.

- global: icebergs could affect indirectly global currents, winds, climatic conditions, sea level systems and carbon output in a cumulative way (Pollard *et al.*, 2009[13]; Geibert *et al.*, 2010[14]). These risks justify a specific environmental protocol for iceberg transportation. Different scales and time frames of icebergs interactions would occur (Table 8.2).

[13] http://140.115.35.249/h/PGGM-new/latest_news/nature07716.pdf
[14] http://www.geos.ed.ac.uk/homes/wgeibert/GBC_Geibert2010_ForWebPage.pdf

Table 8.2 Time Scales of Iceberg Interactions with the Environment in Antarctica

Effect	Scale
Drifting	Short term
Optical	Short term
Cooling	Short term
Scouring	Both short and long term
Tidal regimes	Short term
Biological	Medium term
Duration of winter sea ice	Medium term
Ferruginous sediments	Medium term
Melting pattern	Long term
Current regimes	Long term

Interactions include optical, scouring, cooling, tidal, drifting, thermal, chemical, biological and climatic effects. Optical, scouring, cooling, tidal and drifting interactions would occur on a short term time scale (yearly bases), whereas thermal, chemical, biological and climatic interactions would occur on longer term time scales (decades and more). In the case of an icebergs operating system the range of impacts would depend on the types of transportation operations and on the zones of iceberg transportation operations.

8.4 Expected Environmental Impacts of Iceberg Transportation

In this section I focus on assessing the potential negative impacts of iceberg transportation operations. The anticipated environmental impacts of iceberg transportation were studied by Hull and Ostrander (1973), Lundquist (1977), Epperson (1978), Wadhams and Kristensen (1983), Quilty (1984), Australian Antarctic Division (1985), Wadhams (1990; 1996) and Trombetta-Panigadi (1996).

Lundquist (1977[15]) classified the anticipated environmental impacts of iceberg transportation into two categories: harvesting related impacts to the Antarctic region; and transit-related impacts on the ocean and processing site. They would include the natural interactions of icebergs with the environment such as optical, scouring, cooling, tidal, drifting, thermal,

[15] http://heinonline.org/HOL/LandingPage?collection=journals&handle=hein.journals/narj17&div=4&id=&page=

chemical, biological and climatic interactions and specific iceberg transportation-related impacts. However, iceberg utilisation could have a range of different impacts on the environment (Table 8.3).

Table 8.3 Types of Environmental Impacts associated with Iceberg Transportation

Cause	Air	Water damage	Biodiversity damage	Specific damage
Iceberg Removal	Air temperature	Water temperature	Change in fauna with cooling	Climatic changes Pressure on ecosystems
Iceberg stability			Loss, erosion of the soil, flora and fauna with scouring	
Stronger winds	Wind velocity changes		Indirect flora and fauna impacts	Pressure on ecosystems
Ocean currents		Ocean current velocity changes	Indirect flora and fauna impacts	
Transmitted light			Zooplankton photosynthesis	
Freshwater Influx		Decreased oceanic salinity	Decreased foramaniferal abundance	
Benthic sediment		Increased terrigenous deposits	Plankton, benthic biology	
Infrastructure energy	Photochemical reactions caused by ultraviolet rays, sulfur and nitrogen dioxide	Dissolved metals aluminium, manganese, calcium, magnesium potassium	Toxic metallic ions (aluminium, cadmium) fixation by plants of heavy metals and contamination	Pressure on ecosystems
Operating waste			Additions of organic compounds	Climatic changes
Operating energy	CO_2 emissions		Nutrients reduction to aquatic species	
De-icing	Air purification capacity		Poisonous accumulation in the aquatic food chain of marine ecosystems	Species genetic potential reduction
Accidents/ Spills, hazmats	Air purification and food chain capacity	Modifications of hydrological systems	Contamination	Species genetic potential reduction
Location supplying		Lotic, neritic (continental shelf) and epipelagic (< 100 m) environments Contamination	Disappearance of vulnerable aquatic organism species proliferation of tolerant ones	Tourism potential reduction

There are several types of impacts induced by iceberg transportation such as iceberg removal-related impacts, iceberg stability-related impacts, impacts on winds currents, optical, melting, chemical and biological impacts, impacts related to the energy consumption of the transportation system, impacts related to wastes of the transportation system, impacts related to de-icing of the transportation system, impacts related to the construction of the infrastructure of the transportation system, biological impacts at the destination and impacts related to potential hazards of the transportation system. The species which could be potentially threatened by the iceberg transportation system studied in this thesis generally show higher vulnerability between January and March, which is the breeding season for some of them (Goldman, 1979). Iceberg removal would impact on the global iceberg resource depending on the amount of iceberg utilisation. The utilisation of a small proportion of the total amount of calved icebergs is not expected to affect the capacity of ice shelves to produce icebergs (Denner, 1979). Removing less than 1% of yearly amounts of calved icebergs corresponds to a small volume (8 km^3). Impacts of iceberg transportation operations on global currents, winds, climate, or sea level systems or carbon output would be minor as long as iceberg transportation systems would involve small quantities and utilise limited amounts of fossil fuel energies. The utilisation of a small proportion of the total amount of calved icebergs is not expected to damage the Antarctic climate (Denner, 1979). Hult and Ostrander (1973 p. 1[16]) noted:

> Sea ice formed and thawed each year is thousands of times the total area of icebergs and about then times the mass. This sea ice is a major factor to contend with in the acquisition of icebergs, its moderating influence on the climate (together with that of the continental icecap) is so dominating over that of the icebergs that little climatic effect would be expected even with the complete removal of the total annual iceberg yield.

Iceberg stability issues could affect fish and krill populations by generating a physical blast induced by the capsizing of the iceberg (Goldman, 1979). The capsizing of a tabular iceberg could generate shocks directly or indirectly through large waves.

Optical impacts would be related to the fact that icebergs naturally block sunlight from reaching the ocean floor (Heizer, 1978). Arrigo *et al.*, (2002) reported that surface primary production is negatively affected by optical impacts caused by icebergs. Iceberg harvesting would not affect these natural processes first because the iceberg would drift slowly and melt over a long period and second because the icebergs could be wrapped in transparent bags. Since only a very few icebergs out of thousands or hundreds would be harvested, optical effects could be discounted.

The thermal gradients produced by iceberg melting natural processes can affect fish and krill populations and cause local changes such as fogging from thermal condensation (Goldman, 1979). Iceberg transportation operations that employ a bag to enclose the melting iceberg could decrease local thermal gradients by the wrapping of the iceberg freshwater in bags but these impacts would be minor and transitory as only a very few icebergs out of thousands or hundreds would be harvested. Weeks and Mellor (1978) suggest that a melting iceberg can

[16] http://www.rand.org/pubs/reports/2008/R1255.pdf

produce short term thermal pollution along the transportation route. These impacts would be minor and transitory as the melt water temperature would continuously adapt to the temperature of the water in which it would be transported. Also a substantial part of the thermal impacts on ecosystems would occur before iceberg bagging. The bagging of the freshwater would actually protect krill and fish populations from thermal changes occurring naturally from iceberg melting.

The same analyses apply to impacts due to changes of salinity gradients caused by the fact that the natural freshwater influxes that melting icebergs provide would be trapped in bags. Local saline pollution could occur by decreasing or increasing the salinity levels of sea water and in the case of a major spill of freshwater from the bags, transitory impacts could be expected to result from a localised reduction in salinity (Goldman, 1979; Ryland 1997). Lowest salinity is generally found in surface waters (Smith *et al.*, 2007). Hult and Ostrander (1973) noted that marine ecosystems are resilient and adaptive to a certain range of salinities. A waterbag system that involves the transportation of iceberg melt in a number of smaller bags would minimise the risk of major spills.

The displacement of individuals and/or species, collisions and loss of habitat naturally occur from icebergs scouring (Goldman, 1979). However, icebergs transportation would occur outside of the zones where scouring might take place. Iceberg operating systems could physically disturb benthic communities or zoo and phytoplankton communities with the infrastructures which would be employed such as waterbags, a collar and an iceberg bag surrounded by a net (Goldman, 1979). However, these impacts are likely to be transitory as the infrastructures of iceberg operation could be designed to minimise potential disturbances (from the size of the net to the materials used). Bag manoeuvring and launching processes are likely to have only minor and transitory impacts on seal, fish and krill populations, in accordance with article 1 of Annex II of the Madrid Protocol[17]).

Icebergs contain a number of different chemical components and biological sediments which are released on melting (Lisitzin, 2003). This means there may be biological impacts from transporting icebergs away from the locations within which they normally melt. Melting icebergs release organic and non organic elements. The iron elements contained in icebergs are used by plankton during blooming events (Schwarz and Schodlok 2008[18]; Vernet *et al.*,

[17] http://www.antarctica.gov.au/antarctic-law-and-treaty/the-madrid-protocol/annex-ii-conservation-of-antarctic-fauna-and-flora

[18] http://precedings.nature.com/documents/1706/version/1/files/npre20081706-1.pdf

2009[19]). Iceberg transportation operations could interfere with plankton blooming processes through the removal of the iceberg resulting in a reduction in the iron released into the water and may therefore result in significant impacts on ecosystems that depend on algal blooms. An iceberg operation system is likely to decrease the release of these elements. Biological impacts arising from iceberg transportation at the operating and delivery sites could be important because there is a risk that indigenous species travelling on the operating boat or contained in melt water might be released into the local environments. Appendices B and C of Annex II of the Madrid Protocol[20] discuss these issues and prohibit activities which do not eliminate risks of contamination or invasion. Other potential biological impacts of iceberg transportation on the high seas could be related to fossil fuel consumption through exhaust pollution and possible oil spills. The boats would be designed in accordance with the guidelines of Annex IV of the Madrid Protocol (article 9 and article 10[21]). The impacts resulting from using fossil fuels would be minor and transitory in the iceberg transportation system, based on currents and kites, proposed in the Chapter 7. Risks of oil spills and discharges (which are discussed in Annex IV of the Madrid Protocol, article 1, article 3 and article 12[21]) would be minimised. At the delivery site, impacts relate to fossil fuel pollution from the delivery would be higher but still lower than traditional shipping systems: waterbags transportation systems require six times less propulsion than a ship (Sobinger 1985, see Chapter 10). Following the guidelines of the Madrid Protocol (Annex III, article 1, article 2, article, 5, article 6, article 8, article 9 and article 10[22] and Annex IV, article 5[23]) sea disposal or wastes issues would be addressed through a management plan. Iceberg operating systems would have to use non toxic products in case de-icing processes would be needed. Calcium chloride (CaCl2) Sodium chloride (NaCl) Potassium chloride (KCl) Urea (NH2CO NH2) Calcium magnesium acetate (CMA) are commonly used for de-icing purposes but there are other options such as hot water. In the operating region, de-icing should not be required often (1,400 km away from Amery Ice Shelf (66° S), around 54° S). Alternative and environmental friendly products are available and should be chosen. De-icing is not required for operation occurring in summer or spring (Weeks, personal communication 2011). The environmental impacts of iceberg transportation are summarised in Table 8.4.

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[19] http://polarphytoplankton.ucsd.edu/docs/publications/papers/Vernet_MS_%20Icebergs_Subm042710.pdf and http://icestories.explanatorium.edu/dispatches/tagging-icebergs-from-above/

[20] http://www.antarctica.gov.au/antarctic-law-and-treaty/the-madrid-protocol/annex-ii-conservation-of-antarctic-fauna-and-flora

[21] http://www.antarctica.gov.au/antarctic-law-and-treaty/the-madrid-protocol/annex-iv-prevention-of-marine-pollution

[22] http://www.antarctica.gov.au/antarctic-law-and-treaty/the-madrid-protocol/annex-iii-waste-disposal-and-waste-management

[23] http://www.antarctica.gov.au/antarctic-law-and-treaty/the-madrid-protocol/annex-iv-prevention-of-marine-pollution

Table 8.4 Environmental Impacts of Iceberg Transportation

Disruption	Impact	Effect
Stability	Direct flora and fauna impacts	Change of vegetation with scouring
Rising ice volume	Surface and air temperature	Cooling temperatures change in fauna
Stronger winds	Wind velocity changes	Indirect flora and fauna impacts
Ocean currents	Ocean current velocity changes	Indirect flora and fauna impacts
Transmitted light	Direct flora and fauna impacts	Decreased zooplankton photosynthesis
Sea salinity	Decreased oceanic salinity due to the influx of fresh water	Decreased foramaniferal abundance related to reduced salinity
Infrastructure energy	Dissolved metal pollutants (aluminium, manganese calcium, magnesium, potassium), ultraviolet rays, and sulphur and nitrogen dioxide photochemical reactions	Toxic metallic ions (aluminium, cadmium). Fixation by plants of heavy metals (e.g. lead) and contamination
Operating wastes		Addition of organic compounds
Operating energy		Food reduction to aquatic species
Benthic sediments	Increased terrigenous deposits	Decreased plankton, benthic biology
De-icing	Air purification capacity	Poisonous accumulation in the aquatic chain of marine ecosystems
Spills, hazmats	Air purification and food chain capacity	Contamination of Marine environment
Location supplying	Contamination on lotic environments, neritic (continental shelf) and epipelagic (< 100 m)	Disappearance of vulnerable proliferation of tolerant aquatic organism species

The likely impacts of iceberg transportation could affect several zones in the Antarctic region. Coastal zones could be affected by scouring and other natural processes such as optical, thermal and drifting impacts. An iceberg harvesting operation should not interfere with these processes as most of the ecosystems are located in coastal zones. Coastal zones ecosystems are fragile and vulnerable. Polar ecosystems are fragile in the 300 km zone around the Antarctic continent (Ryland, 1997). The environmental impacts associated with the transportation of icebergs on the high seas affect larger zones. Beyond this zone, in the potential operating zone, beyond 500 km from the coasts, there would still be impacts resulting from operations at the iceberg processing site. However with appropriate practices, these impacts could be reduced to minor and transitory levels. At the operating site, iceberg harvesting and transportation could even help to reduce some of the side effects associated with global warming and climate change:

- directly as the model introduced could have low levels of fossil fuel consumption and therefore low levels of related carbon emissions;
- indirectly as an iceberg water operation could contribute to a decrease in sea level rises. This effect would be very small.

These hypotheses should be the object for further studies to determine the scales of the studied impacts.

8.5 Scales of Environmental Impacts of Transportation

Iceberg transportation can interact with thermal, scouring, optical and mineral impacts of icebergs on the maritime environments. Iceberg transportation can also create potential effects because of iceberg breakage, wastes products, the consumption of fossil fuels, the use of de-icing products, the trapping of minerals contained in icebergs, and risks associated with spills. Fossil fuel consumption or iceberg breakage could cause impacts equal to minor or transitory on the ecosystems at the operating site. Some iceberg operation processes could be designed and managed to reduce their potential impacts on the environment up to acceptable levels. Iceberg water is renewable in specific conditions. The annual iceberg volume that could be transported by iceberg transportation is around 8 km^3/yr, (10% of the annual Antarctic iceberg resource renewability yields and about 1% of the annual Antarctic iceberg resource). Icebergs are a valuable resource which should require appropriate management combined with a formal policy of re-using and recycling of this water. These requirements could be set through law and licenses or permits. Quotas could be applied to regulate the extent of iceberg harvesting, with associated conditions set to reduce the potential environmental impact of the harvesting activity. Table 8.5 shows environmental impacts geographic spread and effects duration.

Table 8.5 Scales of Environmental Impacts

Transportation Impacts	Zone	Impact intensity
Noise and vibrations	Local Scale	Short term medium
Scouring	Coastal	Short term medium
Nutrients Volumes	Global	Short term strong
Cooling	Global	Short term medium
Shadow	300 km	Short term medium
Sea Ice Extent	300 km	Long term none
Sea Level	Global	Short term small
Currents	Global	Long term small
Carbon monoxide, Odours	Local Scale	Short term medium
Smog, Nitrogen oxides, HC/VOC, Particulates, lead	Local and Regional Scale	Short term medium
Acid rain and acid depositions	Regional Scale	Long term small
Climate Change (Carbon dioxide, CFCs)	Global Scale	Long term small
Ozone layer depletion (CFCs)	Global Scale	Long term small
Reduction of fossil fuel reserves	Global Scale	Long term small
Sulphur dioxide, Ozone	Local, Regional and Global Scales	Long term small
Carbon	Global	Long term medium
De-icing of infrastructure, Runoffs	Local and Regional Scales	Short term medium
Accidental and intentional releases	Local and Regional Scales	Long term strong
Marine vessels discharges and spills	Local and Regional Scales	Short term strong
Construction and maintenance of infrastructure	Local and Regional Scales	Short term medium

8.6 Alternatives to Iceberg Transportation Environmental Impacts

To limit environmental damage, several protection measures such as a zoning designed to regulate the type of operations that can take place within certain areas and a means of replacing the elements contained in the removed icebergs could be implemented.

To limit the impacts related to thermal, scouring, optical and mineral effects of iceberg transportation, the operation should occur outside a zone where these impacts could be the strongest. The effects on Antarctic biota and the displacement of individuals and/or species would be minimised at a 300 km distance from shore. Beyond theoretical territorial waters limits the high seas are characterised by a reduced probability of disturbing marine populations (Jenior, 1978; Ryland, 1997). A limited quantity of icebergs could be used corresponding to less than 10% of the number of icebergs naturally drifting each year in a specific operating zone (80 km^3).

In the rest of this chapter the sustainability of the iceberg transportation system studied in Chapter 7 will be assessed and best practices will be discussed.

The project consists of operating icebergs using an iceberg megabag and collecting the meltwater of the iceberg in a collar attached to the bagged iceberg with a net. Then the melt water of the iceberg would be transported using waterbags, currents and kites.

The optical disturbance from the shadow of the icebergs would be transitory and minor as it is already occurring naturally and as the project is based on the use of currents which already are causing the icebergs to drift. The displacement of icebergs would be slow and regular so it would not modify significantly the optical phenomenon induced by the drifting of a similar iceberg that is not being transported.

Iceberg transportation operations would impact the iceberg's nearby environment. The megabag, collar, net installations would cause pollution because of the length of the operation and nearby ecosystems could suffer from limited localised temperature increases and localised chemical releases, which could lead in the long term to a loss of biodiversity. From routine operations in the vicinity of the iceberg localised disturbance of the surface water would occur and there would be loss of surface water habitat, localised pollution, and loss of biodiversity. To deal with these issues, the operations could be based on appropriate technologies developed, adopted and certified like the EMAS 1993 and the ISO 14 001 (Biondi, Frey and Iraldo, 2000; Freimann and Walther, 2001). The use of the operating vessel would be the main source of pollution for the ecosystems. The operating vessel would also be used for waterbag launching. Helicopter operations would also cause pollution but the use of the helicopter is expected to be transitory. The physical presence of the collar and the megabag would potentially interfere with some species, however most of the species in the vicinity of the iceberg are expected to be able to avoid the new infrastructure. Based on operational modelling of Chapter 7, for the transportation of a 25 million tonne iceberg it is estimated that a maximum of 80 t of fuel would be consumed for the vessel operations in the vicinity of the iceberg (arrival, installations, wrapping, stabilising, directing, waterbag handling and launching and departure) which represents less than 20 t. The towing operation of the bags (launching and delivery) and of the material would cause larger petrol consumption which represents less than 60 t (See Chapter 10). It represents less than 200 t of CO_2. These emissions should be rapidly dispersed and diluted by winds and currents and are significantly lower than other water transportation projects or offshore operation of the same scale (between 5 and 100 times lower, see Chapter 10). Emissions would contribute to global warming however these contributions could be negligible on a regional scale.

Ballast water of the operating vessel could release exotic species. Their introduction could cause competition with native species, and in the long term could cause a significant loss of biodiversity within the food chain. The disposal of garbage at sea is prohibited by the Madrid Protocol and by other international law such as MARPOL 73/78 Annex V[24]. Vessels have to establish a garbage management plan and to keep a garbage record book with the disposal types, volumes and routes.

Long shifts and isolation of the crew could affect the crew psychologically. However, an iceberg transportation project would create new employments opportunities and could create commercial benefits (Chapter 10).

Noise levels due to the installation of the iceberg transportation system could disturb marine mammals and affect their behaviours at the proximity of the iceberg. Acoustic monitoring of the behaviours of these animals would provide useful information on the levels of disturbance. However, underwater noise from vessel activity would be of an amplitude too small to cause to cause severe impacts on marine life.

As the icebergs are enveloped in bags it would be important to assess the exchange of chemicals with the environment as bags containing the water would prevent the normal/natural exchange of chemicals that happens when an iceberg melts in the open sea. The natural ecosystem dynamics would be changed by the iceberg transportation proposal as icebergs being enveloped in bags would decrease the amount of chemical exchanges occurring naturally between the iceberg and its maritime environment. Neshyba (1977[25]) doubts that the upwelling produced by icebergs - which results in the melting and the supply of nutrients to the surface layers of the Weddell Sea - would be carried away from the coast.

[24] http://www.nap.edu/openbook.php?record_id=4769&page=263,
[25] http://www.nature.com/nature/journal/v267/n5611/abs/267507a0.html

However, the level of chemical exchanges through upwelling phenomenon could, depending on iceberg melting rates, cause a decrease of nutrients for high sea ecosystems.

A substantial loss of nutrients could occur when the iceberg melts as it drifts in warmer water. The Southern Ocean waters are amongst the richest in the world in plankton. Nitrate, phosphate and silicate are important resources for planktonic communities and iron elements are especially significant for their development. Icebergs contain these elements and are important suppliers for maritime ecosystems (De Baar *et al.*, 1995; Smith *et al.*, 2007). Smith *et al.*, (2007[26]) reported that silicate, phosphate, ammonia and nitrate were not measured in significant amounts in the surface water nearby icebergs. They said that (Smith et *al.*, (2007 p. 1): “free-drifting icebergs can substantially affect the pelagic ecosystem of the Southern Ocean and can serve as areas of enhanced production and sequestration of organic carbon to the deep sea”. Smith *et al.* (2007) reported that “overall the icebergs are raising the biological productivity of nearly 40% of the Weddell Sea’s area”. They found out that the icebergs’ influence was maximum inside a distance of 3.7 km from the iceberg and that beyond 9 km the iceberg influence was minor. Martin and Fitzwater (1988[27]) reported that (1988, p. 1): “Fe deficiency is limiting phytoplankton growth in [these] major-nutrient-rich waters” and Twining *et al.* (2004, p. 1) reported that: “[I]ron (Fe) availability limits phytoplankton biomass and production in large regions of the Southern Ocean”. Iceberg chemical elements removed by iceberg water transportation should be inserted in the ocean. The chemical elements and in particular the iron contained in icebergs used in plankton blooming could be released artificially. A system of motorised buoys could be equipped with a corresponding amount of natural organic and non organic sediments. It could spread them on the same route with a release rate reproducing the release rate of melting icebergs. The buoys could be controlled with remote sensing equipment. Parts of these elements could be collected from the iceberg, at the bottom of the bags by a system of filters.

Some Antarctic animals (such as seals and birds) interact directly with icebergs, predominately using them as habitat. In order to minimise the potential impact resulting from the removal of icebergs, a specific wildlife friendly platform has been proposed (Shick, 2004[28]). A number of these platforms could be assembled where iceberg harvesting takes place.

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[26] http://www.sciencemag.org/content/317/5837/478.abstract,
[27] http://www.nature.com/nature/journal/v331/n6154/abs/331341a0.html See also Martin, 1990 http://www.whoi.edu/cms/files/martin.90_28603.pdf and Martin et al., 1991 http://www.aslo.org/lo/toc/vol_36/issue_8/1793.pdf
[28] http://www.wikipatents.com/US-Patent-6688105/iceberg-utilization-process-improvement, http://www.freepatentsonline.com/6688105.html

The visual impacts of the iceberg transportation operation would not be significant as the operation would occur at a considerable distance from any land.

In order to avoid collisions with other icebergs or maritime objects, a system comprising kites and a tug boat and employing the same types of techniques as the Canadian Ice Services would be used to manoeuvre the iceberg. A kite-driven waterbag transportation system can avoid collisions with other icebergs or maritime objects. Based on these considerations, in case of a collision with a bag, the level of risk of poisoning from an oil spill would be reduced. The iceberg operating vessels would have to comply with IMO regulations. Shipping traffic is increasing significantly in the Southern Ocean particularly the Peninsula area with more than 40,000 tourists per year visiting Antarctica in 2008 (FoEI, 2008[29]; ASOC, 2008[30]) and the risk of accidents affecting humans and the environment fragile Antarctic ecosystems rises consequently (FoEI, 2008; Styner *et al.*, 2008[31]). Recently, in 2007 the commercial tourism vessel MS Explorer sunk (Figure 8.1) and in the M/V Nordkapp grounded at Deception Island, so did in 2006 the M/V Lybov Orlova.

Figure 8.1 The M/S Explorer Sinking (credit BBC 2008, in ASOC 2008, p. 11[32])

The Southern Ocean extreme sea conditions and the remoteness from rescue facilities create unacceptably high levels of risk on the marine environment even at low levels of pollution (FoEI, 2008; ASOC 2009a[33]; Prior, 2009[34]). Five countries (Argentina, Australia, Chile, New Zealand and South Africa) are responsible for Search and Rescue (SAR)

[29] http://www.foei.org/en/resources/publications/miscellaneous/ASOCIMOInformationPaper012508.pdf
[30] http://naturvernforbundet.no/imakerdata/f/1/17/14/0_2401_0/20080415_ASOC_Report_MEPC_57.pdf
[31] http://www.uneptie.org/shared/publications/pdf/DTIx0938xPA-PolarTourismEN.pdf
[32] http://naturvernforbundet.no/imakerdata/f/1/17/14/0_2401_0/20080415_ASOC_Report_MEPC_57.pdf
[33] http://www.asoc.org/storage/documents/ATME/ATME_paper_on_shipping101309.pdf
[34] http://www.asoc.org/storage/documents/Meetings/ATCM/XXXII/managing_antarctic_vessels.pdf

operations are undertaken in Antarctica (CONMAP, 2011 [35]). The absence of a comprehensive system of vessel traffic monitoring for Antarctic vessels establishing, applying and enforcing a regional vessel traffic control system based on a strict regulation with extra precautions it would be necessary to establish ships' routing measures and areas to be avoided (for safety or environmental protection) in the most frequently used regions (Joyner, 1984). The International Association of Antarctica Tour Operators (IAATO) the Council of Managers of National Antarctic Programs (COMNAP), the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) all maintain incomplete list of vessels (CONMAP, 2004[36]; FoEI, 2008). The international environmental NGOs active in Antarctica and the Southern Ocean (ASOC, FoEI, Greenpeace and WWF) support the adoption of a mandatory shipping code addressing ice-strengthening points relevant to all vessels operating south of the Antarctic Convergence to comprehensively address vessel safety. At ATCM XXXII, , a measure was adopted which limits landings from any ship with over 500 passengers (ASOC 2009b[37]; 2009c[38]). In 1990 the IMO defined the Southern Ocean south of 60° S as a "special area" under Annexes I (oil) and V (garbage) under MARPOL 73/78, banning the oily residues, chemicals and garbage disposals (FOEI, 2008a[39]). In 2007 the IMO Assembly adopted a resolution on *Guidelines on voyage planning for passenger ships operating in remote areas* and on July 13, 2007 the MEPC adopted Resolution MEPC.163(56), *Guidelines For Ballast Water Exchange in the Antarctic Treaty Area* (ASOC, 2010[40]). Disposal of wastes, discharges of sewage and black water in the Southern Ocean; the quantity of litter or plastic marine debris in the world's oceans has been steadily increasing over the years. According to Burton and Riddle (AAD, 2011[41]) "[A]bout 10 years ago studies showed that both Macquarie and Heard Islands had accumulated debris on their beaches".

The risks associated with the use of de-icing products and the risks of fuel spills could be further reduced as the project is not based on fossil fuels and is located more than 300 km away from Antarctica. However, intermediate and heavier grade fuel oils will be banned starting in 2011 in the Southern Ocean. According to Spragg (2001) waterbag transportation

[35] https://www.comnap.aq/sar/overview/, see also https://www.comnap.aq/sar/resources/2008_31atcm_ip099_search-and-rescue_en.pdf
[36] https://www.comnap.aq/publications/guidelines/atcm_guidelines_shipping_2004
[37] http://www.asoc.org/storage/documents/IMO/newimo/DE_53-18-3_eNGOs.pdf
[38] http://www.asoc.org/storage/documents/IMO/newimo/ASOC_submission_to_MSC_FINAL2-1-1.pdf, http://www.asoc.org/storage/documents/IMO/newimo/DE_53-18-3_eNGOs.pdf
[39] http://www.foei.org/en/resources/publications/miscellaneous/ASOCIMOInformationPaper012508.pdf
[40] http://www.asoc.org/storage/documents/IMO/ASOC_Polar_Code_Briefing_October_2010.pdf
[41] http://www.antarctica.gov.au/about-antarctica/australian-antarctic-magazine/issue-1-autumn-2001/environment-and-heritage/marine-debris-in-the-southern-ocean

is sustainable and environmentally friendly. The physical disturbances on the high seas are likely to be minor and equivalent to any maritime transportation system of a similar size. The waterbag transportation system would be based on minimal fossil fuel use. The use of non fossil energy is a key point of the new iceberg transportation system described in Chapter 7 as it improves the overall sustainability of the proposal. Waterbags can be made out of recyclable materials, such as polyurethane (made out of diisocyanate with polyol) produced with low energy consumption (ISOPA 2010).

Sanitary wastes of sewage, wash waters and drainage waters, could create long term low levels of impacts from nutrient enrichment, temperature increase and chemical pollution but would be reduced to the area of the iceberg operation. They should be rapidly dispersed. Waste disposal and cleanup could cause potential impacts on marine mammals. Food waste and discharges would have low intensity impacts of organic enrichment. The loss of items, material or equipment at sea would create impacts on biodiversity because of localised pollution and of directly poisoning ecosystems through ingestion.

The discharge of ballast water from vessels in the operating zone may cause the introduction of exotic species contained in the ballast water that disturb native species. However, these waters should be rapidly dispersed. At the delivery site, algal and planktonic populations that could ultimately reside in the melted water of the iceberg should be removed from the iceberg water by a filtering process. The International Convention for the Prevention of Pollution from Ships, 1973, and the Protocol of 1978 (MARPOL) Annex 1[42] provides guidelines for oil wastes water release. In case of a collision a spill of the hydrocarbons contained in the operating boat would have strong impacts on the ecosystems because of the toxicity of hydrocarbons. In high seas, habitats are less sensitive than on coasts and the oil spill would be dispersed more rapidly. It would be expected to cause the death of a large number of species in the area of the spill and to cause international problems because of the unique value of these ecosystems. Seabirds could suffer from intoxication, ingestion, plumage penetration (Munro, 2004). Marine mammals could suffer from ingestion and intoxication. Benthic communities could be strongly affected by oil pollution and this could lead to cumulative effects on the food chain. An oil spill would have lethal toxic effects on plankton. A Polar Code is currently being negotiated within the International Maritime Organization.

[42] http://www.portwaste.com/services/marpol.htm

8.7 Mitigation of Environmental Impacts of Iceberg Transportation

Iceberg transportation can affect the natural thermal, scouring, optical and mineral impacts of icebergs on the maritime environments. Iceberg transportation can also create potential effects because of iceberg breakage, waste products, the consumption of fossil fuels, the use of de-icing products, the trapping of minerals contained in icebergs, and risks associated with spills. However specific practices could mitigate these negative effects. Table 8.6 shows the options to reduce environmental impacts of iceberg transportation.

Table 8.6 Options to Reduce Environmental Impacts of Iceberg Transportation

Transportation Impacts	**Zone**	**Impact intensity on ecosystems**	**Solutions**
Scouring	Coastal scale	Short term strong	Zone
Sea ice extent	Local scale	Long term none	Zone, assessments, permits
Carbon	Global scale	Short term small	Monitoring, assessments, permits
Sea level	Global scale	Long term small	Monitoring, assessments, permits
Currents, winds	Global scale	Short term medium	Monitoring and bagging
Cooling and sea salinity	Global scale	Short term medium	Zone and bagging
Transmitted light and shadow	Local scale	Short term strong	Zone and bagging
Noise, stability and vibrations	Local scale	Short term medium	Netting
Nutrients volumes	Global scale	Short term strong	Mineral inputs and sediment compensation system
Infrastructure and operating energies releasing carbon monoxide, odours, smog, nitrogen oxides, HC/VOC, particulates, lead	Local and regional scales	Medium term medium	Renewable energies based transportation systems, recycling and sustainable materials regulation
Infrastructure and operating energies contributing to acid rain and acid depositions, climate change (carbon dioxide, CFCs), ozone layer depletion (CFCs), reduction of fossil fuel reserves, SO2 emissions, ozone hole	Local, regional and global scales	Long term small	
Construction and maintenance of infrastructure	Local and regional scales	Short term medium	Eco-friendly materials and smart reservoir
Operating wastes	Local and regional scales	Short term medium	Undertake recycling
De-icing of infrastructure, runoffs	Local and regional scales	Short term strong	Eco-friendly materials
Accidental and intentional releases	Local and regional scales	Long term strong	Bagging, bag trains
Marine vessels discharges and hazards	Local and regional scales	Short term strong	Specific emergency planning systems

Amongst the different practices to mitigate environmental impacts of iceberg transportation are a suitable zoning system to ensure that a minimum of species and individual could actually be affected by iceberg transportation, specific designs such as an appropriate netting system, a suitable bagging system, the utilisation of renewable energies based transportation systems, a mineral input compensation system, eco-friendly materials or specific emergency planning systems.

8.8 Transportation Environmental Management

According to Rodrigue Comtois and Slack (2009 p. 279[43]): "[A]n environmental management system is a set of procedures and techniques". It consist of evaluating environmental conditions and issues, undertaking monitoring, assessing risks, impacts and responsibilities on the geographical environments, undertaking environmental management, introducing best practices, auditing environmental impacts reducing techniques, matching and regulating geographical conditions, transport facilities, operations or projects, commercial, technological standards and procedures, financial and technical support with environmental requirements (Comtois, 2009). Three steps are involved in an environmental management system that is specifically directed towards the transportation industry.

1. information gathering to define usable and reliable units of measurement with time and space details, to institute minimum standards and requirements, to adopt an analytical dynamic framework with precise and integrated environmental values and objectives, to determine scientifically the best practices and standards; According to Rodrigue (2009 n.p.[44]) information should be collected on "water, air, soil and all the other components of the physical environment within a precise geographical area";
2. to assess and evaluate risks and impacts. Then once these levels are correlated with environment proximity, a level of exposure to harmful pollutants can be estimated. The likely impacts or consequences of risks need to be assessed. There are several types of impacts of transportation on environmental systems: Direct effects and impacts of transport activities on the environment. Indirect impacts and effects of transport activities on environmental systems have important consequences but are hard to determine. Cumulative impacts on an ecosystem can be additive, multiplicative or synergetic (Krzyzanowski and Almuedo,

[43] http://books.google.com.au/books?id=I-Aq2pXOjnIC&printsec=frontcover#v=onepage&q&f=false
[44] http://people.hofstra.edu/geotrans/eng/ch8en/meth8en/ch8m1en.html

1976[45]). Risk is a combination of uncertainty and negative consequences. Risk assessment involves: hazard identification, risk estimation and evaluation and risk management. According to the different transportation mode, there are different types of indicators;
3. a strategy of operations is set and these standards are integrated within the practices of territorial planning with associated protocols.

Establishing an environmental management system as a means of assessing the environmental impact of a particular transportation project is a complex task. Many difficulties have to be overcome, including a lack of objective and measurable data for evaluating likely impacts, a lack of proscriptive methods easily adapted to novel circumstances, conflicts amongst different jurisdictions and international strategies, and the costs of environmental measures. However, the quantification of a mix of economic, social and environmental costs that are likely to arise from the iceberg transportation proposal considered in this thesis is possible if some simplifications and generalisations are assumed. A specific Environmental Management Plan (EMP) for the iceberg transportation operations would be based on a comprehensive environmental impact assessment of the proposed operations and respond to the specificities of the locations and the operational characteristics of the project. It would more precisely provide instructions for the transportation system itself, guidelines for iceberg transportation operation, principles for the required skills of the crew and include alternative solutions to the operational activities of the transportation system. Assuming the technical feasibility of the iceberg transportation system presented in Chapter 7 it is possible to give an example of an Environmental Management Plan for such a project. More environmental studies and information are needed for the selected region where iceberg transportation operation would be undertaken, namely between the Amery Ice Shelf from where the iceberg would originate (66° S), the region where the iceberg would be operated first around 54° S and WA where the iceberg water would be delivered. These studies should focus on marine mammals, seabirds, surface water habitats, benthic habitats, topography, oceanographic and meteorological data and the potential impacts of iceberg transportation infrastructures, wastes materials and the impacts of iceberg sediments removal. A number of options are available to minimise these impacts. Following these recommendations it is expected that the proposed operations could be undertaken without significant impacts to the environment. However, further studies would help to establish an appropriate iceberg transportation management system.

[45] www.forrex.org/publications/forrexseries/fs26.pdf

8.9 Iceberg Transportation Environmental Management Plan

An environmental management plan to reduce the impact of iceberg operations could be implemented. Its objective would be to maintain the integrity and respect the unique characteristics of the ecosystems (Baron *et al.*, 2002[46]). For the iceberg transportation project studied in Chapter 7, an environmental management plan would include the following activities which would be necessary for the transportation system to be efficient and sustainable:

- choosing operating sites as a function of environmental and accessibility factors. Iceberg detection and reliable environmental data collection are essential for successful operations; Surveying and gathering information about icebergs would help to determine the operating zones and assess environmental damage mitigating practices;
- collecting and sharing environmental data on the local ecosystems;
- monitoring and reporting consumption and emission data of iceberg operations;
- conducting megabag, collar and net installation and operation;
- using specific wildlife-friendly designs such as appropriate collar or netting systems which would help to stabilise the iceberg;
- using suitable bagging systems to enclose the melt water and the iceberg;
- proposing a system to protect the ecosystems using environmental friendly materials and designs;
- establishing comprehensive operational controls for loading, movement of materials;
- training of personnel;
- implementing detailed environmental management operations;
- operating the vehicles, helicopters and vessels with high standards of maintenance;
- reducing the high energy costs of towing by using kites and ocean current drifting techniques (Chapman, 1989);
- developing a detailed waste management plan;
- minimising waste, maximising the re-use and recycling of materials, implementing treatment procedures and establishing practices of segregated storage in appropriate sealed containers and transfer of waste to shore depending on the waste type;
- macerating food waste, in agreement with MARPOL 73/78 Annex V requirements;
- using low toxicity chemicals;
- limiting ballast water discharge. They should comply with International maritime legal requirements;

[46] http://www.biology.duke.edu/jackson/ea02.htm

- establishing the amount and the location of mineral elements that have to be released to compensate for iceberg operations. By surveying plankton blooms, it would also be possible to determine the quantities of physical and chemical elements that would need to be spread in the ocean in order to reduce the impact. The movement and evolution of the icebergs and their undersides could be continuously studied, and the amount and type of nutrients and various elements in the water around the icebergs measured. The best practice could consist of surveying these impacts, estimating the amounts of iron elements that should be released and protecting the plankton blooms with a specific compensation process. A system of motorised buoys could be equipped with a corresponding amount of natural organic and non organic sediments. It could spread them on the same route with a release rate reproducing the release rate of melting icebergs. The buoys could be controlled with remote sensing equipment. Parts of these elements could be collected from the iceberg, at the bottom of the bags by a system of filters. The amounts of mineral elements contained in icebergs vary depending on their origins but generally constitute a small proportion of the iceberg volume (0.001%) (Anderson *et al.*, 1980; Dowdeswell and Murray, 1990; Lazarev, 2002[47]). Therefore, in Antarctica, the annual 5,000 km^3 of icebergs present in the Southern Ocean would contain less than 50 billion t/year of mineral elements. And following similar estimates, for a 2 billion t iceberg, 20,000 t of elements should be released. For a 200 million t iceberg, it is estimated that 2,000 t of elements should be released. For a 25 million t iceberg, it is estimated that about 300 t of mineral elements should be released for environmental purposes and for a 50,000 t iceberg, less than 1 t of elements would have to be released. Table 8.7 presents the proposed volumes of sediments released in compensation for iceberg transportation for different operational scales.

Table 8.7 Proposed Volumes of Sediments Released in Compensation for Iceberg Transportation

Iceberg in tonnes	Sediment in tonnes
5,000 billion	50 million
2 billion	20,000
200 million	2,000
25 million	250
0.25 million	2.5
50,000	0.5

[47] http://books.google.com.au/books?id=TL7R9D8qfb8C&printsec=frontcover#v=onepage&q&f=false

- providing entertainment to the crew and limiting the length of working shifts;
- the aesthetic value of the physical presence of the iceberg transportation infrastructure could benefit from a regulation in respect to the universal value of the Southern Ocean landscapes. Regulation against inappropriate advertising could be useful;
- implementing specific comprehensive emergency planning systems;
- training of key personnel in emergency planning systems.

8.10 Response Actions in Case of Accident of Iceberg Transportation

A specific emergency plan would be needed to deal with accidents associated with or arising from the iceberg transportation system. It would be based on an initial emergency response including emergency rescue and dispersants response kits against spills. Key personnel would be trained to respond effectively to hazards. Use of spare waterbags could be important part of an emergency protocol, particularly to reduce spill risks.

8.11 Costs of the Environmental Impacts of Iceberg Transportation

Externalities refer “to activities of a group that have unintended consequences, positive or negative, on other groups” (Rodrigue and Comtois, 2009[48] n.p.). Negative externalities are often supported by societies as transportation infrastructure, construction and maintenance are often subsidised by the public. Reducing economic costs practices traditionally creates profits to the detriment of environments by discounting potential impacts on ecosystem). In the economical analyses of iceberg transportation reviewed in Chapter 10 environmental externalities of iceberg transportation will be studied. According to (Rodrigue and Comtois, 2009[49] n.p.) “the assessment of environmental externalities of transportation involves multiple causes, effects and consequences”. The complexity of the economical integration and the poor media coverage of environmental impacts and health issues explain why they are underestimated. Kenworthy and Newman (1990) established the major categories of environmental externalities as being energy, quality of air, water, materials, waste, land, and biodiversity. A specific environmental management plan for iceberg transportation operation of the iceberg transportation system studied in Chapter 7 could reduce environmental disruption to minor levels especially when compared to other activities supplying the same

[48] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/ch8c1en.html
[49] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/table_externtbl.html

amounts of water. The benefits of such a plan will be estimated in Chapter 10 and the operational environmental practices will be detailed now. The inclusion of environmental externalities within economic analyses of transportation has become common practice (Button, 1990). If all elements of the environmental management plan are actively incorporated into new iceberg transportation projects, then there can be confidence in the economic and environmental feasibility of utilising Antarctic icebergs as a freshwater resource. If the negative externalities costs associated with the sediment loss would be effectively balanced by the proposed compensation process, the overall negative externalities costs of the project would be marginal when compared to other activities supplying the same amounts of water (this is further assessed in Chapter 10). The operational stages of iceberg transportation could have positive impacts on the environment:

- improved transportation operation and transportation systems consuming less energy "that reduced environmental externalities are likely to have positive economic, social and environmental consequences" (Rodrigue and Comtois, 2009[50] n.p.);
- iceberg transportation could also participate to the replenishment of stressed environments at the arrival site with substantial environmental benefits.

The iceberg transportation system studied in Chapter 7 could create substantial savings related to better environmental practices based on the new water supply at the delivery sites. An increase in water resource volume could generate:

- the regeneration of land water resources;
- a decrease of associated health service costs and a decrease of the losses in biological diversity associated with the pollution caused by land water transportation supply systems;
- an increase in revenues from recreational values of land water resources and a related increase in rent values of land water resources;
- a decrease of treatment costs and cleanup costs of available water resources at the delivery sites.

8.12 Conclusion

The Antarctic Treaty System Environmental Impact Assessment (EIA) process is critical in identifying potential environmental impacts of the iceberg transportation system. In this

[50] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/ch8c1en.html

chapter I have assessed potential impacts of iceberg transportation. These were ranked according to their perceived level of impact, as either:

- less than minor or transitory;
- equal to minor or transitory;
- greater than minor or transitory.

Exposure risks could be minimised and the risks of contamination could be reduced as:

- the populations affected by the operations are limited to high seas ecosystems;
- the reduced time of dilution of the water, as the water is bagged and is non toxical (harmless micro-organisms);
- the reduced zone of transportation over relatively small distances (from the ATT to Australia);
- the reduced time of transportation, and the sustainable transportation process itself (Banister and Button, 1993);
- using radar could help to detect and further protect endangered species ;
- Iceberg water is very pure and would not require substantial levels of treatment to be drinkable.

For these reasons an iceberg transportation process might only have minimal harmful effects on the environment. However, iceberg utilisation would still be likely to cause other harmful effects. These effects could be addressed by a specific environmental management plan. Furthermore guidelines for the iceberg transportation system studied in Chapter 7 would reduce adverse impacts to minor levels. They consist mainly of:

- an operating process based on bags;
- the use of a stabilising net;
- strict operating rules;
- a specific transporting system based on currents and kites limiting the use of polluting fossil fuels;
- a compensation process designed to replace nutrients lost from iceberg removal;
- using sustainable and environmentally friendly materials for waterbag transportation.

It could therefore be possible to establish standards and best practice for iceberg transportation systems by proposing rules for protecting, maintaining and restoring marine ecosystems. These rules include the use of an important specific process to compensate and release part of the chemical components of the icebergs. This addresses micro and macro organisms, as well as microscopic mineral elements which could impact in a cumulative way on wildlife and habitat. Measuring exposure levels, it appears that icebergs transportation systems following these guidelines would not lead to ecological modification (Byun *et al.,* 1979).

In economic terms, for iceberg water transportation systems using non fossil energy negative externalities due to transportation pollution would be reduced which represents a potential major outcome. The costs induced by these externalities would need to be compared with the costs of other types of freshwater supply operating techniques in order to demonstrate the utility of a sustainable iceberg transportation process. A specific cost-benefit analysis of these externalities could further help to establish quotas for environmental protection against the problems associated with transport operations and elaborate appropriate environmental pricing policies.

Having just examined the technical and environmental requirements for future projects to be feasible and sustainable, in the last three substantive chapters of the thesis I focus on the legal, economic and political concerns on iceberg transportation systems.

Chapter   Law of Antarctic Iceberg Transportation

Figure 9.0 Claims over Ice (credit Le Petit Journal, 1909 p. 1)

Is it possible to conceive a production structure which
could allow natural obstacles and social obligations to
occur without alienating minds and bodies?
(Translated from Weil, 1935 p. 94)

Chapter Law of Antarctic Iceberg Transportation

The transportation of icebergs from the AAT to WA raises some critical international and national legal issues. The legal aspects relating to the exploitation of Antarctic icebergs and their transportation to dry regions have been studied by several authors (Lundquist, 1977; Joyner, 1992 and 1999; Rothwell, 1996 and 1997; Trombetta-Panigadi, 1996). The legal definition of icebergs is complex and has important implications for resource use and rights in Antarctica, the Southern Ocean and the Australian Exclusive Economic Zone (EEZ). The objective of this chapter is to assess the international and Australian legal context of iceberg transportation. The chapter commences with an introduction to the Antarctic Treaty System (ATS) and the principal instruments that govern iceberg transportation. The second part examines the role of the Law of the Sea Convention (LOSC) and how iceberg acquisition could be undertaken in territorial seas and the high seas. The third part of the chapter examines the relevant Australian legislation and presents an assessment of the aspects of domestic law most relevant to iceberg transportation. Finally, assuming that the type of iceberg transportation system studied in this thesis is feasible, guidelines for a new regime specific to this type of iceberg transportation system are provided.

9.1 The Antarctic Treaty System

The development of the ATS depended on sovereignty issues. A number of criteria have been used to justify claims to territorial sovereignty: prior discovery, the formal ownership process, geographical proximity, explorations, legislative measures, the sector principle, and according to Beck and Dodds (1998[1] p. 16) “the permanent occupation through scientific bases” (Triggs, 1997[2]). During the 1950s the search for a solution to the Antarctic 'problem' of claims to territory led to the development of Article IV of the Antarctic Treaty (Watts, 1986; Jackson, 1995; Charney, 1993). According to Beck and Dodds (1998[3] p. 17): “[T]he territorial question was evaded through a non-solution freezing individual legal positions”. The Antarctic Treaty was signed on 1 December 1959 and came into effect on 23 June 1961. The Treaty was initially signed by 12 nations (Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, South Africa, the USSR, the UK and the US) that were active in the International Geophysical Year (IGY). Seven countries had territorial claims, namely

[1] http://www.gg.rhul.ac.uk/cedar/cedar-papers/paper26.pdf
[2] http://journals.cambridge.org/action/displayAbstract;jsessionid=7B73D8B79A0CDF27CBC469F6CB29CD25.tomcat1?fromPage=online&aid=4467252
[3] http://www.gg.rhul.ac.uk/cedar/cedar-papers/paper26.pdf

Argentina, Australia, Chile, France, New Zealand, Norway, and the UK. The USSR and the US reserved their right to make a claim in the future (Figure 9.1).

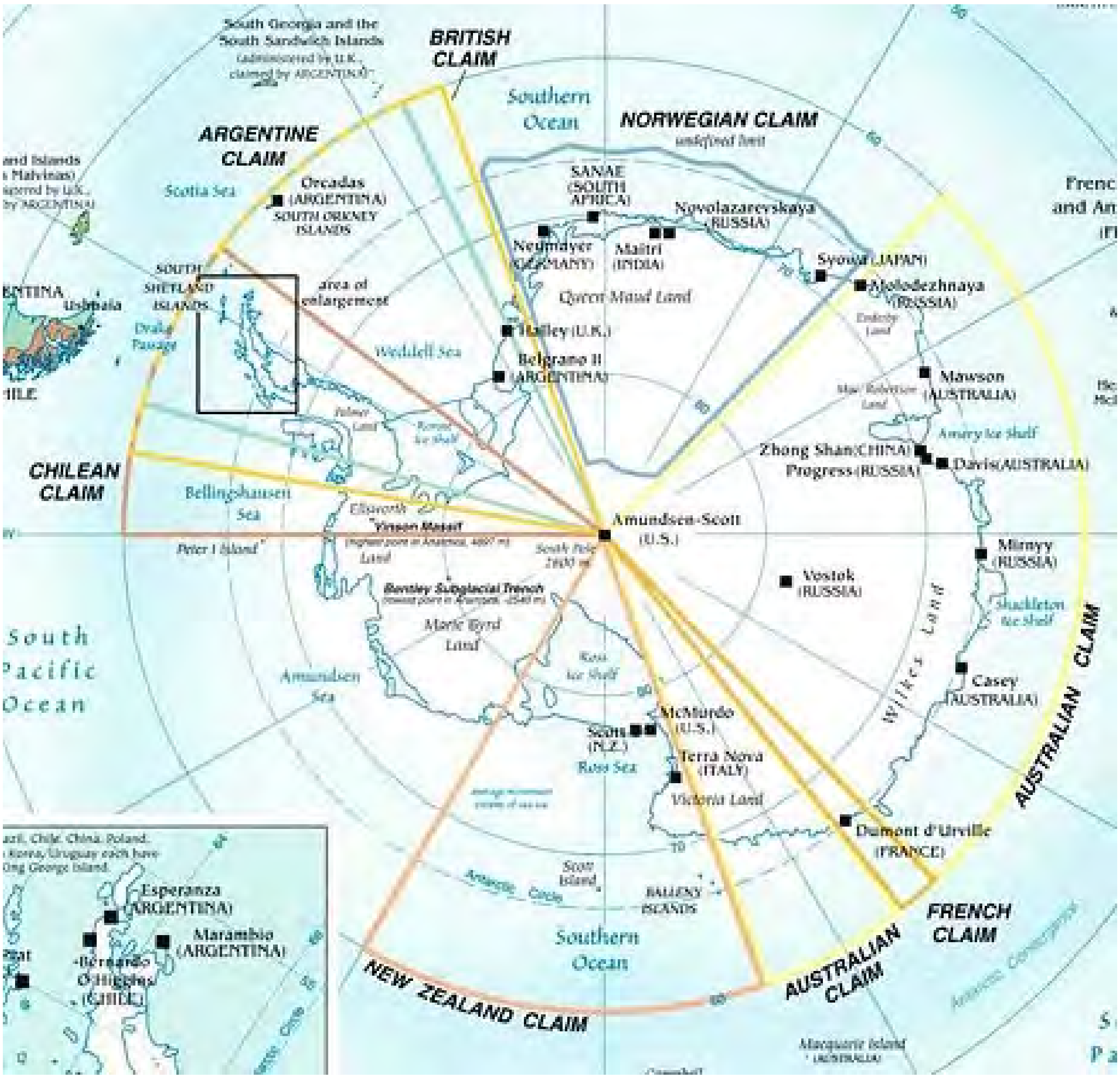

Figure 9.1 Antarctic Claims (credit University of Texas University[4] 2009 n.p.)

In summary the 14 articles of the Treaty (AAD[5], 2010 n.p.):

[4] http://en.wikipedia.org/wiki/File:Antarctica.CIA.svg
[5] http://www.antarctica.gov.au/antarctic-law-and-treaty/our-treaty-obligations

- “stipulate that Antarctica should be used exclusively for peaceful purposes; military activities, such as the establishment of military bases or weapons testing, are specifically prohibited”;
- “guarantee continued freedom to conduct scientific research, as during the IGY”;
- “promote international scientific cooperation including the exchange of research plans and personnel, and requires that results of research be made freely available”;
- “set aside the potential for sovereignty disputes between Treaty parties by providing that no activities will enhance or diminish previously asserted positions with respect to territorial claims, provide that no new or enlarged claims can be made, and make rules relating to jurisdiction”;
- “prohibit nuclear explosions and the disposal of radioactive waste”;
- “provide for inspection by observers, designated by any party, of ships, stations and equipment in Antarctica to ensure the observance of, and compliance with, the Treaty”;
- “require parties to give advance notice of their expeditions”;
- “provide for the parties to meet periodically to discuss measures to further the objectives of the Treaty”; and
- “put in place a dispute settlement procedure and a mechanism by which the Treaty can be modified”.

The ATS includes the Antarctic Treaty and related agreements on the Antarctic. Antarctic Treaty Consultative Meetings (ATCM) are held annually and represent the international management institution of Antarctica. In 2010, there were 48 Antarctic Treaty nations[6] (Scully, 1991; Berguno, 2000).

The Antarctic Treaty defines Antarctica as the lands south of 60°S latitude including the ice shelves (The Antarctic Treaty[7], p. 4). All the seas and the freshwater of the Antarctic continent are covered by the Treaty. The Treaty seeks to ensure that Antarctica remains “a

[6] http://www.ats.aq/e/ats_treaty.htm
[7] http://www.ats.aq/documents/ats/treaty_original.pdf

zone of peace, a continent for science and a special conservation area[8]" (Quilty, 1990; de Cesari, 1996; Beintema, 1998). According to the AAD[9] the Antarctic Treaty System (ATS n.p.):

> includes recommendations, measures, decisions and resolutions of [ATCMs] ... relating to:
>
> - scientific cooperation;
> - protection of the Antarctic environment;
> - conservation of plants and animals;
> - preservation of historic sites;
> - designation and management of protected areas;
> - management of tourism;
> - information exchange;
> - collection of meteorological data;
> - hydrographic charting;
> - logistic cooperation; and
> - communications and safety.

According to Beck and Dodds (1998 p.17):

> [D]uring the last three decades, resource management was a major preoccupation for Treaty parties assuming the clear identification of ownership for the purposes of regulation over exploitation or conservation and distribution of benefits.

In the late 1970s and early 1980s, the ATS began to establish guidelines for mineral use in response to research that exposed the resource potential of the continent (Westermeyer *et al.*, 1989[10]).

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[8] http://www.kike.nl/kike_antarctic_policy.html, see also http://www.ats.aq/documents/ats/treaty_original.pdf
[9] http://www.antarctica.gov.au/antarctic-law-and-treaty/our-treaty-obligations
[10] http://www.fas.org/ota/reports/8926.pdf

The resources of Antarctica are divided in the ATS into three main components: marine living resources, mineral resources and resources derived from the natural environment, including wilderness and scientific values. A number of agreements were passed or proposed in order to protect these values including:

- the Convention for the Conservation of Antarctic Seals1972;
- the Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA), in 1988, proposed a detailed mineral regime through recommendations IX-1, X-1, and XI-1 to regulate mineral use (Berkman, 1992; 2001; Ryland, 1997). It was not signed by all Consultative Parties and therefore did not enter into force. According to Ryland (1997 p. 52): "[H]owever, external pressure on the ATS, including a 1986 United Nations Resolution to place a moratorium on mineral talks, led to the breakdown of CRAMRA (Beck, 1987[11])"; the Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol[12]) was signed on 4 October 1991, and entered into force on 14 January 1998[13]. The Madrid Protocol prohibits all mineral resource activity and declares "Antarctica as a natural reserve for peace and science" (Article 2, see also Herr, 1996; 2000; Orheim, 2000). The main objective of the Protocol is "to protect the Antarctic environment and its related ecosystems" (Article 2[14]), "to preserve the aesthetic values, the natural state and the research of Antarctica, "essential to understanding the global environment" (Article 3[15]). Freshwater resources in Antarctica are regulated by the Madrid Protocol for environmental protection and are located in zones defined as special zones of conservation (Article 5[16]). Cooperation between parties (Article 6[17]) and environmental impact assessments (Article 8[18], Annex I; Article 3) obligations are explained, and their implementation is overseen by the Committee for Environment Protection (CEP) (Rothwell, 1996; 1997 and 2002; Joyner, in Oude Elferink and Rothwell, 2001[19]). This Protocol had five original annexes: Environmental Impact Assessment, the Conservation of Antarctic Fauna and Flora, Waste Disposal and Waste Management, Prevention of Marine Pollution and Area Protection and Management.

[11] http://polarmet.mps.ohio-state.edu/ASPIRE_99/report/report.htm
[12] http://www.ats.aq/documents/recatt/Att006_e.pdf
[13] Council of Managers of National Antarctic Programs. COMNAP, https://www.comnap.aq/publications/treaty/madrid_protocol_with_annexes1-6/view
AAD, http://www.antarctica.gov.au/antarctic-law-and-treaty/the-madrid-protocol
[14] http://www.ats.aq/documents/recatt/Att006_e.pdf
[15] http://www.ats.aq/documents/recatt/Att006_e.pdf
[16] http://www.ats.aq/documents/recatt/Att006_e.pdf
[17] http://www.ats.aq/documents/recatt/Att006_e.pdf
[18] http://www.ats.aq/documents/recatt/Att006_e.pdf
[19] http://books.google.com.au/books?id=RAOOlYTEzUEC&printsec=frontcover#v=onepage&q&f=false

In 2005 Annex VI on the 'Liability Arising from Environmental Emergencies' was adopted[20]. Icebergs have been discussed in the ATS. The problem of their potential use has been raised at several ATCMs. At ATCM XI, in Buenos Aires in 1981, the commercial exploitation of icebergs was discussed. During this meeting it was determined that icebergs should not be considered a mineral resource (ATCM XI meeting, Section 2.1.3, Paragraph 6, Notes 53 and 56). The use of ice was subject to the provisions of the Protocol, other than Article 7. The Special Antarctic Treaty Consultative Meeting IV on Antarctic Mineral Resources (1982 in Wellington), stated that: "iceberg operating issues should be discussed regarding their potential environmental impacts on Antarctic ecosystems".

In 1983, at the Canberra ATCM XII, a recommendation was made that Antarctic ice should not be treated as a 'mineral' (Prescott and Schofield, 2005). In 1985, at the Brussels ATCM XIII, the use of ice was discussed in view of future developments which were not detailed. Some of the potential uses could have concerned iceberg transportation operations as it was still an important area of study in the early 1980s. At the ATCM XV (Paris 1989) the use of Antarctic ice was raised again, taking into account the possible impact of iceberg harvesting on the environment and the "desirability that commercial exploitation of ice does not occur prior to examination of the issues involved" (Francioni and Scovazzi, 1996 p. 229). Recommendation XV - 21 on the 'Use of Antarctic Ice' was adopted. The ATCM recommended that information be exchanged "on the feasibility of [the] commercial exploitation of icebergs relevant technologies and possible environmental impacts" (ATCM XV-21 Paris, 1989[21]). Finally, at the ATCM XVI in Bonn in 1991, the consultative parties scheduled the inclusion of these recommendations in the ATCM. However, the question was not discussed then, or at the ATCM XVII in Venice (1992), ATCM XVIII (1994) in Kyoto nor at the ATCM XIX (1995) in Seoul without any clear reasons (Trombetta-Panigadi, 1996[22]).

Adopted in 1991, the Madrid Protocol prohibits activities related to mineral resources (except for scientific research) for 50 years within the ATS territory. However, icebergs have a variety of legal interpretations. Icebergs have been included in mineral elements within the ATS, but have not been determined as a mineral element. However the nature of what is considered a 'mineral' has never been clearly specified by the ATS (Ryland, 1997). Indeed,

[20] http://www.ats.aq/e/ep_liability.htm
[21] http://www.ats.aq/devAS/info_measures_listitem.aspx?lang=e&id=190
[22] http://books.google.com.au/books?id=cIFAZPBKKuwC&pg=PA225&lpg=PA225&dq=Trombetta-Panigadi,+1996&source=bl&ots=ULHcg4dUpS&sig=XwzOCBDK9dFM0WeS_mCu8uw1WV4&hl=en&ei=zd8GTZ2RFM7NrQfbvZivCQ&sa=X&oi=book_result&ct=result&resnum=1&ved=0CBUQ6AEwAA#v=onepage&q=Trombetta-Panigadi%2C%201996&f=false

the possibility that ice might be an Antarctic resource remains an ignored subject.

Icebergs could be defined as both, marine and land natural environmental resources, a non-living physical resources, solid mineral water resources, liquid water resources, hazardous floating objects, and floating resources.

Even if the regulation of non-living mineral resources in Antarctica is not clear (Chamoux, 1978; Beck, 1986; Ryland, 1997) and if it is generally accepted that icebergs are not included in the ATS, it would be possible today to operate icebergs within the ATS territory with an environmental impact assessment. It could be considered that the Protocol virtually provides a status of exception for the 'operation' of icebergs, since June 2006 (ATCM XXVIII when the Annex VI of the Protocol was finalised) recommendation on the operating of icebergs restates its conditional status to an environmental impact assessment (AAD, 2010). The Final Act of the conference at which the Protocol was adopted was quite clear in its interpretation of the status of ice in the context of the minerals ban: The Meeting noted that the harvesting of ice was not considered to be an Antarctic mineral resource activity; it was therefore agreed that if the harvesting of ice were to become possible in the future, it was understood that the provisions of the Protocol, other than Article 7, would apply (Final Act of the Eleventh Antarctic Treaty Special Consultative Meeting);

9.2 Iceberg Transportation and Marine Legal Regimes

The 1982 Law of the Sea Convention (LOSC) is an international agreement that resulted from a number of United Nations Conferences on the Law of the Sea (UNCLOS) held over more than two decades. According to Le Gresley (1993 n.p.[23]) the LOSC corresponds to: "United Nations Conferences held... in order to codify various aspects of the law of the sea" regarding "territorial division of the seas".

The 1958 Geneva conference UNCLOS I on sailing in deep oceans and related territories (border zones, fishing zones and protection zones) and UNCLOS II in 1960 led LOSC to several treaties on:

- the Territorial Sea;

[23] http://dsp-psd.pwgsc.gc.ca/Collection-R/LoPBdP/BP/bp322-e.htm

- the Contiguous Zone;
- the High Seas;
- the Continental Shelf and
- the conservation of living resource.

A third UN conference took place from 1973 through 1982. In December 1982, the UNCLOS III was convened at Montego Bay (CMB) (Jamaica). A hundred and nineteen States ratified it. It eventually entered into force in 1994, by the international authority for marine grounds and human common patrimonies (Rothwell, 2000[24]; Oude Elferink and Rothwell, 2001[25]). The LOSC includes provisions covering anticipated developments which are not yet technologically feasible (Le Gresley, 1993[26]). According to Le Gresley (1993 n.p.): "[A]s well, a significant body of customary and treaty law outside the LOSC pertains to the law of warfare, pollution control, and general security matters and may become applicable in a marine setting".

The Secretary General of the United Nations assumes the responsibility of ratification and accession and the UN organises meetings of states party to the Convention. However, the UN does not participate directly in the Convention. An international court of law was created for all the outside national zones, border zones and Exclusive Economic Zones.

Under the LOSC, according to Le Gresley (1993 n.p.[27]): "states have some sovereign rights to [a] ... portion of the sea adjacent to their ... coastline". "[S]ome portion of the sea, the seafloor and the sea-bed are shared as part of the common heritage of mankind."

States have the obligation "to preserve the seas and accommodate the needs of other States … Customary international law, developed by State practice rather than treaties, remains an important source" of legal developments (LeGresley, 1993[28]; Germani, 2003). The International Maritime Organisation, the International Whaling Commission, and the

24 http://www.ejil.org/pdfs/11/3/544.pdf, http://eprints.utas.edu.au/2661/19/17_Rothwell.pdf
25 http://books.google.com.au/books?id=RAOOlYTEzUEC&pg=PA337&lpg=PA337&dq=Oude+Elferink+and+Rothwell,+2001&source=bl&ots=FS2vw2zcJb&sig=-rOe0wvHus8cqbJfO5O13Ek45dA&hl=en&ei=leUGTYLnOs_NrQfu-a3aDQ&sa=X&oi=book_result&ct=result&resnum=4&ved=0CC0Q6AEwAw#v=onepage&q=Oude%20Elferink%20and%20Rothwell%2C%202001&f=false
26 http://dsp-psd.pwgsc.gc.ca/Collection-R/LoPBdP/BP/bp322-e.htm
27 http://dsp-psd.pwgsc.gc.ca/Collection-R/LoPBdP/BP/bp322-e.htm
28 http://dsp-psd.pwgsc.gc.ca/Collection-R/LoPBdP/BP/bp322-e.htm

International Seabed Authority take also an active part in these developments. According to the COMNAP (2011, n.p.[29]):

> "Under international maritime and aeronautical agreements, Rescue Coordination Centres (RCCs) of 5 countries (Argentina, Australia, Chile, New Zealand and South Africa) share responsibility for the coordination of Search and Rescue (SAR) over the Antarctic region. (…) Arrangements and systems in place are primarily based around Search and Rescue Regions (SRRs) and Rescue Coordination Centres (RCCs) established under the auspices of the International Maritime Organisation (IMO)".

Figures 9.2a and 9.2b show the zones of RCC and SAR.

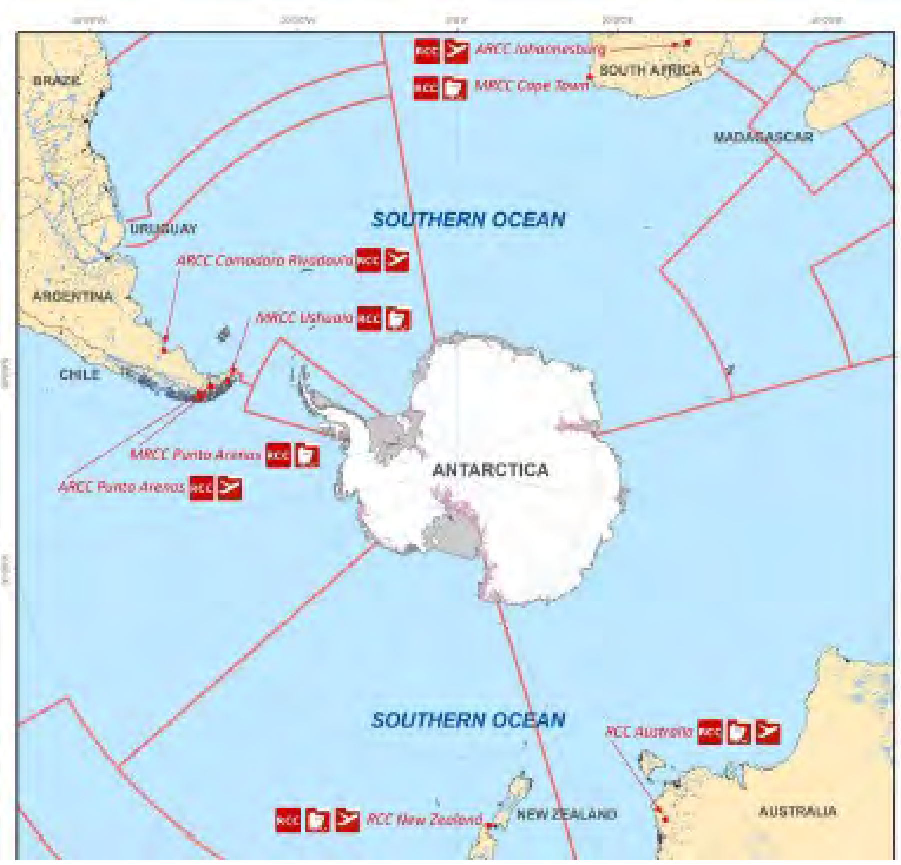

Figure 9.2a Maritime and Aeronautical RRCs and Maritime SRR Boundaries (credit : CONMAP, 2008[30] p. 15)

[29] https://www.comnap.aq/sar
[30] https://www.comnap.aq/sar/resources/2008_31atcm_ip099_search-and-rescue_en.pdf

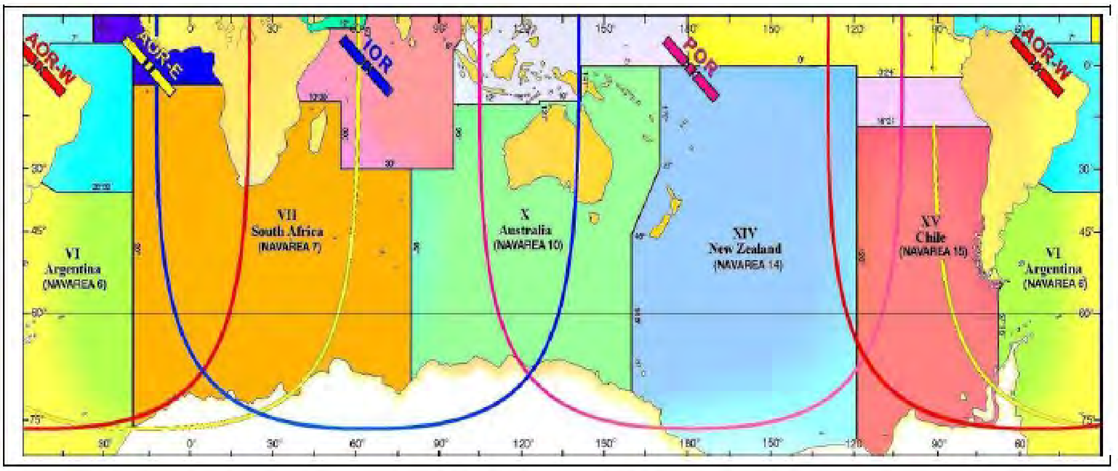

Figure 9.2b Navigational Areas (NAVAREAS) (credit: CONMAP 2008, p. 18)

9.3 Marine Law Discussion

The floating ice shelves of the Antarctic continent are subject to discussion. The potential issues that could affect iceberg are however underestimated and icebergs do not have any specific legal status under the LOSC. Iceberg transportation would have to respect the general rules of the marine law concerning sailing and maritime operations.

On the high seas, sailing is a fundamental right provided fishing activities and preservation of underwater cables are respected. The Montego Bay Convention also provides rules that govern artificial islands, offshore stations, scientific research and military observations; whereas dangerous goods transportation is covered by the SOLAS Convention ratified in 1974 (LeGresley, 1993). Ice covered areas are referred to in the LOSC Part XII, under Article 234[31] on the protection and preservation of the marine environment (Harsson *et al.,* 2003[32]; Sohnle, 2004).

Presently, Article 234 of Section 8 of part XII of the LOSC[33], regarding the protection and the preservation of the marine environment, deals only with coastal ice covered zones and stipulates that the coastal nations must prevent and reduce any pollution of the marine environment in the borders of the EEZ.

[31] http://www.un.org/Depts/los/convention_agreements/texts/unclos/UNCLOS-TOC.htm, http://www.gmat.unsw.edu.au/ablos/ABLOS10Folder/S3P2-P.pdf
[32] http://www.gmat.unsw.edu.au/ablos/ABLOS03Folder/PAPER4-1.PDF
[33] http://www.un.org/Depts/los/convention_agreements/texts/unclos/part12.htm

According to the LOSC (Part XII, Article 234, UN CMB, 1982 n.p.[34]):

> Coastal States have the right to adopt and enforce non-discriminatory laws and regulations for the prevention, reduction and control of marine pollution from vessels in ice-covered areas within the limits of the exclusive economic zone, where particularly severe climatic conditions and the presence of ice covering such areas for most of the year create obstructions or exceptional hazards to navigation, and pollution of the marine environment would cause major harm or irreversible disturbance of the ecological balance. Such laws and regulations shall have regard to navigation and the protection and preservation of the marine environment based on the best available scientific evidence.

This article is specifically directed towards managing seasonal changes in ice covered regions that represent a real danger for shipping. According to Harsson *et al.* (2003 p. 1[35]):

> [T]he Law of the Sea to determine the extent of continental shelves start from base lines bounded by the outermost land/sea margin. [Normally] ... the base lines are drawn from immovable rock to rock but this is not always the case in the polar areas. Here the outer boundaries of 'terra firma' may be glaciers or ice shelves with fronts that can exhibit significant changes in position.

The same authors reported that (2003 p. 3):

> The coasts of Antarctica are nearly all ice covered [and] ... [c]ompared to other continents there are very few offshore islands. Approximately half the circumference of the continent is in the form of rock outcrops or glaciers that calve off where they start to float, and which do not change their position significantly. The other half consists of ice shelves.

Harsson *et al.* (2003) proposed to draw base lines around Antarctica using satellite data. There is no mention of the territorial sea baseline issue in ice-covered areas (O'Connell, 1982; Rothwell, 2002; Mangone, 1987). So the LOSC does not cover Antarctic icebergs. However, beyond Article 234 ice has a *res nullius* status (Sohnle, 2004), which means that icebergs could potentially be operated with no limits because of the lack of any precise regulation. The *res nullius* status of ice suggests that icebergs may be freely harvested by

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[34] http://www.un.org/Depts/los/convention_agreements/texts/unclos/part12.htm
http://www.hri.org/docs/LOS/part12-7.html
[35] http://www.gmat.unsw.edu.au/ablos/ABLOS03Folder/PAPER4-1.PDF

any State, taking into account appropriate environmental provisions. Outside the EEZ, as icebergs are moving, their harvesting could be subject to claims from different national laws, depending on their origin. Trombetta-Panigadi (1996 p. 247) suggests treating icebergs "as natural resources which are freely appropriable and, therefore, no longer belonging to the coastal State in whose waters they originated". Icebergs could be owned by their first finder or in the case of iceberg transportation by their operators. However, one could argue that icebergs belong to a natural hydrological cycle and that they are natural water resources belonging to maritime hydrological systems. These systems could be protected by the environmental obligations of the LOSC (Lefeber, 1990 and 2000; Joyner, 1992 and 1998[36]; Watts, 1992; Rothwell, 1996[37] and 1997; Trombetta-Panigadi, 1996). If icebergs are part of the common heritage of mankind, States would have the obligation to preserve them and accommodate the needs of other States (Lundquist, 1979). The frozen state of icebergs and their temporal and seasonal characteristics do not avoid their definition by the sea law (Rothwell and Elferink 2001[38]; Kaye, 2004[39]; Prescott and Schofield, 2005). The LOSC is the convention that, at least indirectly, would regulate iceberg transportation. If icebergs were acquired and harvested on the high seas then they would not be subject to any regulations stemming from any EEZs considerations, or any unrecognised territorial claims. In the absence of coastal sovereignty, the coastal waters of Antarctica can be treated as high seas (Beck, 1986, 1990). It would be possible today to operate icebergs within the high seas with an impact assessment (UN CMB, Part XII). The iceberg transportation system studied in Chapter 7 and operated in the conditions reported in Chapter 8 would have probably minor or transitory related environmental impacts and would therefore be legally feasible under both the LOSC and the ATS (Zuccaro, 1978; Quigg, 1983; Schwerdtfeger, 1988; Joyner, 1992[40]).

9.4 Iceberg Transportation under Australian Law

Under the LOSC, "when icebergs are located in a territorial sea they seem to fall within the right of sovereignty of the coastal state" (Trombetta-Panigadi, 1996 p. 246). Within the EEZ,

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36 http://trove.nla.gov.au/work/34869144?selectedversion=NBD9078936 and http://findarticles.com/p/articles/mi_qa3854/is_199910/ai_n8876305/
37 http://books.google.com.au/books?id=xslq-KwOpqoC&printsec=frontcover#v=onepage&q&f=false
38 http://books.google.com.au/books?id=RAOOlYTEzUEC&pg=PA38&dq=THE+EXPLOITATION+OF+ANTARCTIC+ICEBERGS+IN+INTERNATIONAL+LAW&hl=en&ei=KuEGTefDJ4umugPsq6jNBg&sa=X&oi=book_result&ct=result&resnum=8&ved=0CFEQ6AEwBw#v=onepage&q=THE%20EXPLOITATION%20OF%20ANTARCTIC%20ICEBERGS%20IN%20INTERNATIONAL%20LAW&f=false
39 http://www.gmat.unsw.edu.au/ablos/ABLOS03Folder/PAPER4-2.PDF
40 http://www.brill.nl/default.aspx?partid=227&pid=19007

national governments could be free to control the operation of icebergs. International obligations have to be ratified by domestic law to take effect. Within the territorial sea, the coastal state has sovereign rights to resources found in the water column (and icebergs by extension). According to Lundquist (1977[41] p. 23): "The coastal state's rights would be exclusive, unless licensing arrangements could be negotiated by foreign nationals". In Australia, these domestic laws follow the guidelines of the ATS and apply in Antarctica and refer to activities that are permitted, accessible zones, and environmental impact assessment processes (Gebers, 1995; Ensminger *et al.*, 1999). The main Australian laws related to Antarctica are:

- the Australian Antarctic Territory Acceptance Act 1933;
- the Australian Antarctic Territory Act 1954;
- the Antarctic Treaty Act 1960;
- the Antarctic Treaty (Environment Protection) Act 1980;
- the Antarctic Marine Living Resources Conservation Act 1981;
- the Antarctic Treaty Environmental Protection (ATEP waste management regulations) 1994;
- AAT Criminal Procedure Ordinance;
- the Environment Protection and Biodiversity Conservation Act (EPBC) 1999;
- the Antarctic Seals Conservation Regulations 1986 as of 11 June 2007.

Australia claims 42% of Antarctica (Jabour, 2006; Rothwell and Scott, 2008). However, in Antarctica, claimant states have not generally extended their claims into the 200 nautical mile EEZ. The Australian EEZ is based on the Australian territorial claim to Antarctica. Australia has asserted an Australian Antarctic maritime zones seas where these laws are applicable (Figure 9.3).

[41] http://heinonline.org/HOL/LandingPage?collection=journals&handle=hein.journals/narj17&div=4&id=&page=

Figure 9.3 Australia's Marine Jurisdiction (credit Geoscience Australia[42] 2008, n.p.)

In July 1994 Australia declared up a 200 nautical mile EEZ around the AAT. It submitted its continental shelf zone borders beyond 200 nautical miles to the Commission on the Limits of the Continental Shelf in 2004 and it told subsequently the Commission not to examine, the AAT-related data (Jabour, 2012). According to Kaye[43] (2004 p. 10): “[T]he harvesting of an iceberg within a declared EEZ of an Antarctic claim would raise questions under Article IV of the Antarctic Treaty and of sovereignty”. According to Kaye (2003, p. 5 See also Bush, 1982): “[N]o claimant State in the Antarctic expressly claims pack ice, except Chile, which has indicated that it has all types of ice in its sector”. There are no common agreements on the existence of Antarctic sovereign states at the moment (Joyner, 1990[44]).

This is an important issue regarding iceberg transportation. For example in the Northern Hemisphere, Newfoundland, as a coastal province of Canada, has awarded licenses for iceberg operation since 1999 to private water and alcohol producers. In this case the

[42] http://www.ga.gov.au/image_cache/GA17424.gif
[43] http://www.gmat.unsw.edu.au/ablos/ABLOS03Folder/PAPER4-2.PDF
[44] http://lawlibrary.unm.edu/nrj/31/1/11_joyner_ice.pdf See also Joyner and Chopra 1988 http://books.google.com.au/books?id=Wj2XYqEDiVsC&printsec=frontcover#v=onepage&q&f=false

icebergs are operated by Newfoundland for the purpose of exploiting the non-living natural resources of the Canadian EEZ (Article 56 of the UNCLOS[45]). The coastal State, within its EEZ, has exclusive harvesting rights over icebergs. However, Denmark contested the ownership of the icebergs claimed by Newfoundland on the basis that these icebergs had originated from Greenland glaciers (Geon, 1997).

According to Geon (1997[46] p. 288): “[T]hree regimes of water rights acquisition: riparian rights, the prior appropriation and administrative allocation” [concern] “the general principles of national water law that might be applicable to iceberg appropriation”

According to Geon (1997) the riparian regime would not be practical in the context of iceberg acquisition. The prior appropriation doctrine stipulates that the water can be used at any given location. This regime needs widespread investment in iceberg utilisation technologies and would not be compatible with the ATS. The administrative allocation of iceberg operation rights would be compatible with both the ATS and the LOSC. Geon (1997 p.301) concludes that:

> [I]n the absence of other guidance, and in combination with existing rules of international law, an examinations of these regimes acts only as a framework to help address an undecided, and as yet unripe, question of Law.

Concerning iceberg administrative allocations, the Australian Senate Standing Committee on Natural Resources has recommended to the AAD since 1985 to undertake a feasibility study to assess the resource potential including economic viability of icebergs as an alternative for freshwater (Schwerdtfeger, 1985). The AAD argued that the removal of icebergs from the Antarctic environment would not create a permanent and adverse impact because of the small number potentially removed for freshwater purposes relative to the total volume of icebergs generated each year (Australian Senate, 1984, p. 629; 1985. 711). However there is no specific Australian legislation or regulations that deal with iceberg transportation. Since the early 1990s, all levels of government in Australia have committed themselves to the

[45] http://www.un.org/Depts/los/convention_agreements/texts/unclos/closindx.htm

[46] https://litigation-essentials.lexisnexis.com/webcd/app?action=DocumentDisplay&crawlid=1&doctype=cite&docid=19+Mich.+J.+Int'l+L.+277&srctype=smi&srcid=3B15&key=ff4a0b1ab2cd87574f163f02ebb1525f, http://direct.bl.uk/bld/PlaceOrder.do?UIN=038043535&ETOC=RN&from=searchengine, http://heinonline.org/HOL/LandingPage?collection=journals&handle=hein.journals/mjil19&div=12&id=&page=

concept of ecologically sustainable development[47]. A complex network of policies and laws exist to support this, particularly in natural resource management (Padgett and Kriwoken, 2001; Fallon and Kriwoken, 2005). Nevertheless, the existing legal framework offers environmental impact assessment provisions under Australia's Antarctic Treaty Environmental Protection, Act and the Environment Protection and Biodiversity Conservation Act (EPBC).

According to Fallon and Kriwoken (2002, p.75[48]): "[I]n Australia, the AT(EP) Act implements obligations at the national level arising from the Madrid Protocol and the 1964 Agreed Measures for the Conservation of Antarctic Flora and Fauna". According to Fallon and Kriwoken (2002, p. 76[49]) the AT(EP) Act protects: "Antarctic flora and fauna and the Antarctic environment through a permit system, a regime of protected areas and the EIA process". The AT(EP) Act reproduces the Madrid Protocol's instructions for the process of Initial Environmental Evaluations (IEE) and Comprehensive Environmental Evaluations (CEE). The AAD administrates the AT(EP) Act. The AT(EP) Act is the fundamental instrument for approval. It is used for 95% of activities of the AAT (Fallon and Kriwoken, 2002).

The EPBC Act ensures a strong level of protection by establishing an EIA procedure based on a 'significance test' for actions which could affect significant aspects of the national environment. According to Fallon and Kriwoken (2002, p.74[50]): "World Heritage properties; Ramsar listed wetlands; listed threatened species and ecological communities; listed migratory species; protection of the environment from nuclear actions; and the Commonwealth marine environment"; and a heritage legislation package (Fallon and Kriwoken, 2002). The marine environment of Antarctica as well as international waters, are protected by the EPBC Act. Under this Act, the Department of Environment and Heritage (DEH), and the Environment Minister are responsible for approving the EIA. According to Fallon and Kriwoken (2002, p.75[51]):

> There are five levels of assessment: assessment without the preparation of a Public Environmental Report (PER) or Environmental Impact Statement (EIS), a PER, an EIS, a public inquiry, and a one-off accreditation of a State or Commonwealth process.

[47] http://www.aph.gov.au/house/committee/laca/antarctica.pdf
[48] http://eprints.utas.edu.au/2995/1/Environmental_Impact_Assessment_Antarctic_Treaty.pdf
[49] http://eprints.utas.edu.au/2995/1/Environmental_Impact_Assessment_Antarctic_Treaty.pdf
[50] http://eprints.utas.edu.au/2995/1/Environmental_Impact_Assessment_Antarctic_Treaty.pdf
[51] http://eprints.utas.edu.au/2995/1/Environmental_Impact_Assessment_Antarctic_Treaty.pdf

There are precise consultation periods for concerned persons and agencies for commenting the EIAs draft before the publication of final documents.

Both the AT(EP) and EPBC Acts are designed to help decision making for specified activities. They require the completion of an EIA before any activity that could lead to significant environmental impact is undertaken, including an assessment of cumulative and indirect impacts. They also specify examination periods for draft submissions and they set thresholds for establishing significance levels for environmental impacts (Fallon and Kriwoken, 2002 p. 80). All activities planned in the AAT are subject to be explained regarding their characteristics and features that could cause environmental impact. In the domestic context EIAs are undertaken at several levels; First, a preliminary assessment will determine the likely impact; if the planned activity will have a good chance to have less than a minor or transitory impact on the environment the activity will proceed. If, however, the impact is likely to be minor or transitory, then an IEE is prepared by each operator. The objective of the IEE is to determine all the options to assess and measure as accurately as possible the potential impacts of operations (Ensminger, McCold and Webb, 1999; O'Riordan, Cameron and Jordan, 2001). The draft IEE is circulated for public comment and forwarded to selected agencies (DEH, the Australian Heritage Council, COMNAP), professionals, experts and non-government organisations. Beyond the public consultation period of four weeks and once all comments received have been adequately addressed in the revised EIA the AAD's Assessing Officer advises the Minister's Delegate who can then award approval (Fallon and Kriwoken, 2002 p. 78). Finally, a CEE is undertaken when impacts are likely to be greater than minor or transitory. They represent a more detailed version of an IEE and gives provisions for a higher level of investigation. According to Fallon and Kriwoken (2002 p. 90[52]):

> Once the draft CEE is released for public comment, the AAD must publish a notice in the *Commonwealth of Australia Gazette* to ensure the public has 'at least' 28 days to comment after publication of the notice. The draft CEE is also sent to all signatories of the *Madrid Protocol* for comment, the CEP and made publicly available to all ATCPs at least 120 days before the next biannual ATCM. Foreign parties must respond within 90 days from being sent the draft CEE. The final CEE should address and include a summary of comments received on the draft document. Notice of any decisions relating thereto and any evaluation of 'significant' impacts in relation to the advantages of the proposed

[52] http://eprints.utas.edu.au/2995/1/Environmental_Impact_Assessment_Antarctic_Treaty.pdf

activity should be made publicly available at least 60 days before commencement of the activity.

CEE includes:

a. non-technical summary;
b. description of the proposed activity;
c. description of the existing environment;
d. description of methods and data used to predict impacts;
e. analysis of expected impacts;
f. alternatives;
g. mitigation measures;
h. monitoring of impacts;
i. response action in case of accident;
j. audit arrangements;
k. conclusion;
l. contact name and address; and
m. external consultation and proponent response.

According to Fallon and Kriwoken (2002[53] p. 77) an EIA depends on the impacts measured: "[A]lthough an activity may be determined as having 'less than a minor or transitory impact on the environment', approval to proceed may be given subject to certain conditions aimed at minimising potential impacts". According to Fallon and Kriwoken (2002[54] p.78):

> [T]he Australian approach for the preparation of PAs is that activities can be determined as either engineering and logistical activities or scientific activities submitted as part of a formal scientific proposal. On average, Australia assesses 80 to 90 activities at the PA level each year. Approximately 60 per cent of these are scientific research activities, with the balance being logistics related.

[53] http://eprints.utas.edu.au/2995/1/Environmental_Impact_Assessment_Antarctic_Treaty.pdf
[54] http://eprints.utas.edu.au/2995/1/Environmental_Impact_Assessment_Antarctic_Treaty.pdf

An Australian project of iceberg water transportation would have to comply with Australian laws and lead to more specific rules more relevant to the legal and political boundaries towards the AT boundary (Figure 9.4).

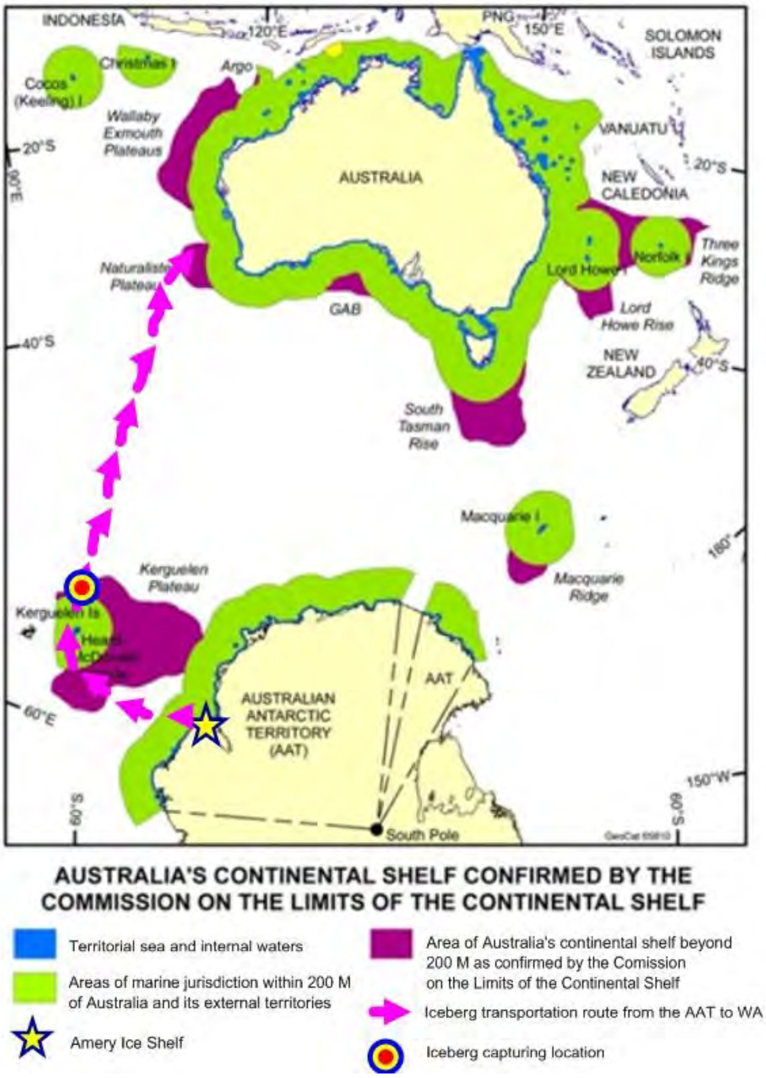

Figure 9.4 Australia's Maritime Zones (credit from Geoscience Australia[55] 2010, n.p.)

Research on iceberg transportation could be a growing area of scientific interest for the Australian Antarctic research program in the next decade.

9.5 Iceberg Transportation Legal Future

[55] http://www.ga.gov.au/image_cache/GA13557.gif

There is no international convention or declaration that relates specifically to the acquisition, transportation or use of icebergs (Foreman, 1993[56]). Resource law does not address icebergs, just as there is no international law relating to water resources. Even established precedent has no bearing on the acquisition of iceberg rights because no state has yet acquired a large iceberg (Quilleré-Majzoub, 2009[57]). However, opportunities exist to develop criteria for iceberg exploitation.

Table 9.1 lists different regimes that would affect iceberg operations. These regimes, with their largely compatible obligations, could provide a basis for development of laws or regulations relating to the harvesting of icebergs.

Table 9.1 Obligations for the Different Regimes Concerning Iceberg Operation

	ATS	**UNCLOS**	**International Law**
Obligations	Environmental Assessment	Protection of the Environment	Protection of the Environment
Zones	Prohibits activities in ATS Zones	Ownerships in EEZ	First Arriving

The LOSC and the ATS may circumscribe a potential right to acquire icebergs by a State (Joyner, 1984, 1986[58]; Oxman, 1986; Molenaar, 1998; Oude Elferink and Rothwell, 2001).

However even within the most restrictive interpretation of the different legal frameworks, it would be possible today to operate icebergs within the ATS territory as well as within the neighbouring high seas (UN CMB Part XII[59]) on the basis only of an impact assessment. However to clarify this issue, it would be beneficial to design a specific iceberg law pertaining to the resource-rich waters below 60^{o} S surrounding Antarctica. This specific law should be compatible with the recently reaffirmed Antarctic Treaty (Kaye, 2003). Geon (1997) suggests that a legal framework for iceberg acquisition should draw on three sources: international conventions; international customs as evidence of general practice; and the general principles of law.

[56] http://www.auilr.org/pdf/7/7-4-3.pdf
[57] https://www.judicialview.com/Law-Review/Environmental/Dairy-Polar-Icebergs:-Reflections-on-the-Rules-Governing-Future-Exploitation-of-Freshwater-Locked-Up-in-Icebergs/24/13992, http://sqdiorg.com/volumes/pdf/20.1_quillere-majzoub.pdf
[58] http://heinonline.org/HOL/LandingPage?collection=journals&handle=hein.journals/cintl19&div=19&id=&page=
[59] http://www.un.org/Depts/los/convention_agreements/convention_overview_convention.htm

A recommendation focused on the utilisation of Antarctic icebergs and the impacts of that utilisation would have to be formulated by establishing relevant criteria (Ryland, 1997). One solution would be an international legislative framework adopted to provide clear global and local guidelines to protect associated ecosystems. The icebergs originate in the Antarctic waters, therefore their legal status must be considered under the ATS or a compatible rule (Ryland, 1997).

The Antarctic is being viewed increasingly in environmental terms. The idea that in theory the Antarctica should become a World Park raises practical difficulties regarding definition, modes of management, monitoring and policing (Rothwell, 1990). In particular, the concept raises the question of balancing the various activities in Antarctica, including the priority to be attached to conservation as compared to science, fishing and tourism. According to Beck and Dodds (1998 p.20[60]): “Triggs has argued that common heritage and the ATS are not necessarily irreconcilable concepts, particularly as the latter embodies various common heritage elements, like peaceful use and environmental protection”.

Icebergs can have another status if they are considered as an environmental resource. An appropriate legal status of icebergs would integrate the different legal aspects of the ATS and marine laws including the LOSC.

9.6 New Legal Status

Icebergs, clouds and open waters do not have national legal status. Freshwater is an ecological element (a natural resource), a social resource (shared as essential for life), and a political one (a resource that implies solidarity). As in the case of the Newfoundland dispute, the origin of icebergs and the environmental impacts related to the harvesting of icebergs would be raised by the requirements of the ATS and the LOSC. Geon identified three areas of inquiry: acquisition, transport and landing (Geon, 1997). It would be possible to find a definition compatible with these requirements, if iceberg could be considered as environmental freshwater mineral resources. The legal status of an ice water operating system is determined by the physical characteristics of the ice, its origins, its locations, the operating techniques involved, environmental impacts, and social uses and values.

The physical characteristics of icebergs determine the range of impacts of iceberg

[60] http://www.gg.rhul.ac.uk/cedar/cedar-papers/paper26.pdf

operations. Iceberg freshwater is both a mineral resource and an ecological element (a natural resource), with thermal, mineral, physical and biological impacts.

Essentially icebergs are bodies of ice which have calved from an ice shelf part of the high seas which may also be ‘land’, capable of occupation which moves and dissolves into the sea (Orrego-Vicuña, 1988). The status of the ice could depend on its stability. According to Cripps (1996 n.p.[61]) due to its perennial nature: [an] “iceberg may be considered part of the high seas whereas an iceberg shelf is merely an extension of the land”. It is similar to the explanations of Joyner (1990 p. 224[62]) which justifies it: "because it has become temporarily solid and partially capable of physical occupation".

Icebergs are also biological resources for the sea environments. As international environmental resources, icebergs would have a *res communis* (they belong to everyone) dimension. Icebergs operations would therefore have limits in respect to their effects and roles on the polar environments. They are crystallised metamorphic and sedimentary mono-mineral rocks (depending on whether they form in marine or continental environments). Icebergs are non-living, renewable and mobile water resources (Chamoux, 1978). More significantly, iceberg drafting makes an important contribution to marine sedimentary record.

The transportation of icebergs would require ensuring the protection of the environment, including arrangements for dealing with navigation problems. Both the ATS and the law of the sea provide environmental obligations for any project of iceberg operation. Disturbances levels (less, equal or greater than minor or transitory) and renewability times of icebergs would have to be defined (according to land time scale of ice, marine time scale of calving, as not all the icebergs are usable, melting rhythms and rhythms of uses). Harvesting of icebergs would have negligible impact on sea levels (Chapter 8). A sustainable iceberg water transportation system (with a negligible impact on the environment) could slightly minimise environmental impacts of iceberg transportation (Ryland, 1997; O’Riordan, Cameron and Jordan 2001).

To design a suitable means for transporting iceberg water, legislation is needed with technical, environmental, economical, ethical and political parameters (Rolston, 2003[63]). Several key issues must be studied to develop an efficient, safe means of ice harvesting.

[61] http://www.alsa.asn.au/files/acj/1996/cripps.html
[62] lawlibrary.unm.edu/nrj/31/1/11_joyner_ice.pdf
[63] http://lamar.colostate.edu/~hrolston/Env-Ethics-Antarctica.pdf

Different technical solutions can be proposed (zoning, choosing between small and large icebergs, breakthroughs in ice operating as well as in enveloping techniques) with environmental studies in order to reduce or to avoid any potential impacts on the environment (Lyons, 1993; Duppies, 1996; Gebers, 1996; Ryland, 1997; Ensminger, McCold and Webb, 1999). A treaty of operating, sharing and preserving the resource appears as a necessity.

9.7 Iceberg Treaty Principles

Fundamental principles relating to iceberg freshwater transfers need to be incorporated in international and national conventions in order to create a safe environmental regime. Iceberg transportation projects have to be considered in the context of promoting socio and economic well-being of societies (OECD N° 2003/1). The use of the resource has to be undertaken in accordance with fair principles, which could be incorporated in the international and national legislations, as a socio-environmental sustainable condition (Rolston, 2003[64]).

The operators in charge of iceberg transportation would have to conduct an Environmental Impact Assessment and act in accordance with the requirements of the Law of the Sea during transportation.

Commercial access to icebergs for harvesting could be allocated by quotas determined following environmental studies. The sustainability of icebergs operation as well as the use of their water as a resource would be an important issue. A sustainable iceberg water supply system could enhance the responsibility towards the present and future generations and in due respect with the precautionary principle, which aims to protect the human health from any potential risks (Orrego Vicuña, 1988[65] p. 82; Wolfrum, 1992; Hansom and Gordon, 1998). The sustainability concerns the operation of icebergs as well as the use of the water resource in order to maximise the responsibility towards the present and future generations and to respect cautionary principles, which aims to protect the human health from any potential risks (Wolfrum, 1992; Hansom and Gordon, 1998). An appropriately integrated

[64] http://lamar.colostate.edu/~hrolston/Env-Ethics-Antarctica.pdf
[65] http://books.google.com.au/books?id=jBk9AAAAIAAJ&pg=PA179&dq=THE+EXPLOITATION+OF+ANTARCTIC+ICEBERGS+IN+INTERNATIONAL+LAW&hl=en&ei=KuEGTefDJ4umugPsq6jNBg&sa=X&oi=book_result&ct=result&resnum=3&ved=0CDcQ6AEwAg#v=onepage&q=THE%20EXPLOITATION%20OF%20ANTARCTIC%20ICEBERGS%20IN%20INTERNATIONAL%20LAW&f=false

management of iceberg resources would determine the technical feasibility, the economic profitability, the social values, the repartitions and the environmental integrity of iceberg transportation projects (OECD N° 2003/1). Such an integrated management of iceberg resource would help to:

- use the abundance of the resource appropriately, and to participate to sustainably develop territorial activities;
- design projects on appropriate scales;
- minimise environmental damage;
- condition the supply in fresh water by a sustainable management of this supply (reducing wastes and loss, pollution control, reuses of the water);
- share the income of the resource operation between all the structures of the beneficing community.

Optimal operating conditions should be further assessed. A strong focus should be made to expand on the research presented in the First International Iceberg Utilisation Conference, and research with the goal of future iceberg harvests should commence upon recommendation approval.

These principles could help to define legal related guidelines such as operating zones, operating quotas, operating rules and environmental impacts assessments obligations.

9.8 Operating Zones

A natural scale of study and management of projects needs to be defined to minimise the potential negative impacts and abusive risks of iceberg transportation. It appears that polar flora and fauna are affected by icebergs flux. The spatial impact of icebergs utilisation could affect several impact zones (Homan, 2006[66]): Antarctica, transportation routes, and the destination ecosystems.

The displacement of individuals and/or populations can be avoided by utilising icebergs occurring 200 miles offshore beyond territorial waters (Jenior, 1978) and specific equipment. Iceberg operating would be restricted to defined zones beyond 200 miles offshore in compliance with any nation's EEZ. We saw that the unique circumpolar geography of Antarctica gives ample access to iceberg resources, and that Antarctic icebergs have

[66] https://maritimejournal.murdoch.edu.au/index.php/maritimejournal/article/viewFile/21/44

suitable characteristics in terms of volume and of physical characteristics to be operated for freshwater utilisation. More specifically, two specific sites have been identified for harvesting. The Amery Ice Shelf can supply Australia and the Eastern Hemisphere with icebergs (Kelley, 1978); the Ross Ice Shelf is in prime position to supply South America, Africa, the Western Hemisphere and Australia (Kelley, 1978). Assuming that an iceberg transportation project could be undertaken, operating in the zones specified above would ensure minimal if any environmental disturbance in the zone of the Antarctic Treaty Protocol (1991). Figure 9.5 show the zones of potential environmental disturbance related to an environmental protocol. The iceberg capturing and the compensation program would occur at the border of the ATS zone.

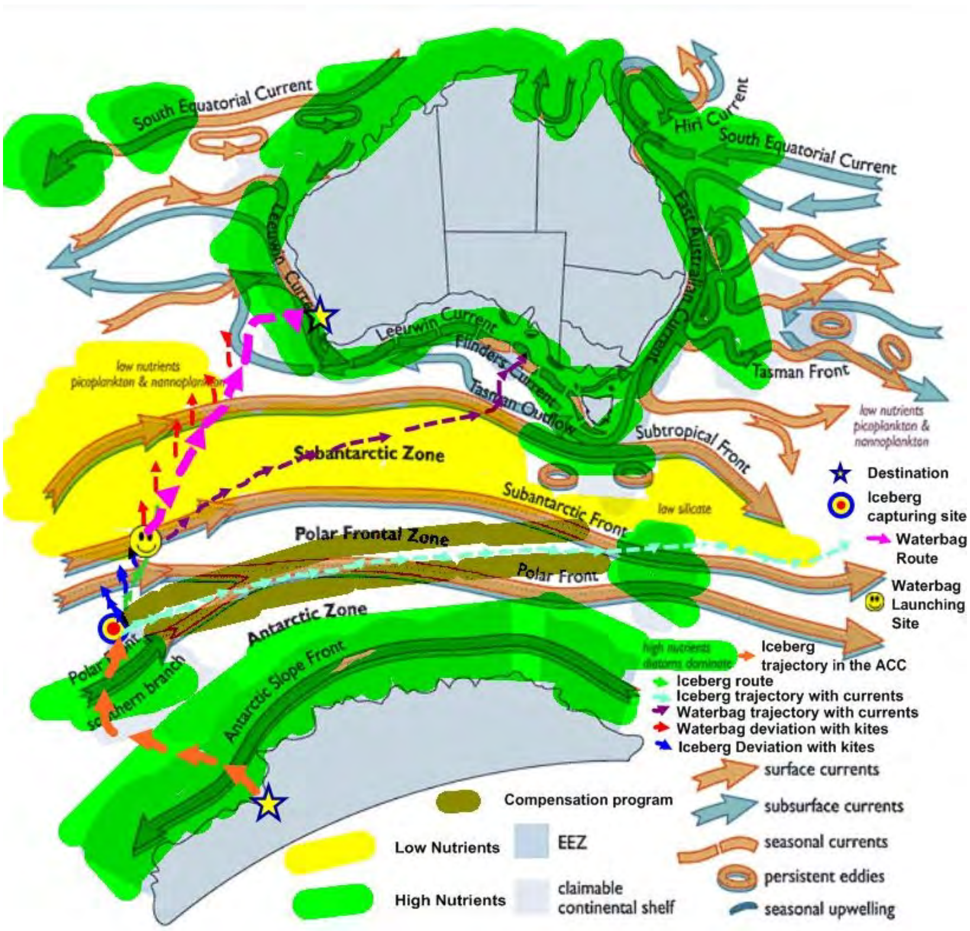

Figure 9.5 Zones of Potential Environmental Disturbance Related to an Environmental Protocol (credit: from Edmonds, 2007[67])

[67]www.waterengineeringaustralia.com.au/pdf/wea_0809.pdf

9.9 Operating Rules

The characteristics of the technical operations would also determine the range of impacts. A sustainable iceberg operation project must have only minor or transitory effects on the environment. For example, the thermal pollution across a transportation route represents a brief, short term impact (Weeks and Mellor, 1978). On the model of fishing, objective legal definitions could be used as a basis for developing environmental tools. The questions of iceberg ownership and of the transportation of icebergs through territorial seas, and associated issues of liability and pollution depend primarily on the origin and the location of the iceberg. According to Ryland (1997 p. 52[68]): "[T]he legal implications of iceberg ownership and the liabilities involved with an accident must be addressed (Bishop, 1978)". If thermal or mineral pollution, caused by the iceberg melting, is observed, the coastal State affected could proscribe the passage of icebergs or impose specific requirements under its power to regulate navigation and pollution (Article 211 LOSC[69]). The slow moving icebergs would interfere with existing transportation on the high seas under the international law of "freedom of navigation" (Article 87 LOSC[70]). Accidents could occur from collision between the transportation device and another ship, or between the iceberg and a ship or due to calving during transportation. Such accidents would be governed by the maritime fault rule fixing damage liability among the colliding vessels. This freedom would have to be exercised with due regard to the interests of other States in navigation and fishing (Ryland, 1997). The iceberg could be treated as a ship, registered under the same flag of the device of which it is towed. The State that would own the device would be responsible for damages caused by the iceberg. According to Ryland (1997 p. 53): "[T]his provision eliminates any potential discord over iceberg ownership". Ryland (1997 p. 53) reported also that:

> Finally, strict transportation guidelines must be established to avoid any infringement of international or local shipping laws (Kish 1973). These guidelines must include provisions for assessing the liability for loose icebergs in transit, or ecological damage incurred by the harvest or transport.

A special regime for the towing or sailing of an iceberg or a train of icebergs would be necessary. Operating techniques would be defined in respect with the environment. On top of this zoning, sustainable technologies of transportation and impact management were

[68] http://polarmet.mps.ohio-state.edu/ASPIRE_99/report/report.htm
[69] http://www.un.org/Depts/los/convention_agreements/texts/unclos/closindxAgree.htm
[70] http://www.un.org/Depts/los/convention_agreements/texts/unclos/closindxAgree.htm

proposed in this thesis including, storage containers to minimise the contact of icebergs with the local marine ecosystems of their destination such as bags, the use of natural energies such as wind and currents, and a minimisation of physical and chemical impacts by a specific compensation system (see Chapter 7 and Chapter 8).

9.10 Environmental Impact Assessment

An Environmental Impact Assessment under Australian Law for Iceberg transportation from Antarctica to Australia would depend on harvesting-relating impacts, transit-related impacts, and processing site-related impacts on both the renewability of the resource and the ecosystems.

Icebergs harvested from Antarctica are a renewable resource with no present possibility of over-usage (Bishop, 1978). However their renewability should be measured: icebergs have temporal dimensions both on geological (long duration) and ecological (short duration) time scales (Ryland, 1997). The geological one is based on their formation, which in the case of tabular icebergs is 500,000 years. Land time scale of ice, marine time scale of calving (as not all the icebergs are usable), melting rhythms and rhythms of uses occur at different scales of time. At an appropriate scale the operating of icebergs could be classified as a non consumptive use, as the resource is renewable and as it can be flexibly operated from different places. Icebergs offer a large renewable freshwater resource which needs to be protected with a legal system. And the system of zoning and permits could address this issue.

The ecosystems of the fragile cold regions must be highly protected and the impacts on these ecosystems must be monitored. As shown above, iceberg harvesting has the potential to disrupt the delicate Antarctic ecosystem but this disturbance as well as the displacement of individuals and/or populations can be avoided by utilising icebergs occurring 200 miles or more offshore beyond territorial waters (Jenior, 1978). Any assessment yielding more than a minor or transitory impact to any marine ecosystem would be denied (Ryland, 1997; O'Riordan, Cameron and Jordan, 2001).

An annual environmental assessment should be gathered by each operator, in order to protect the marine ecosystems, the transportation zone ecosystems, and the destination marine ecosystem and to measure the impacts precisely. In the case of Australia, the AAD could undertake the assessments (Wood, 1995; Duppies, 1996; Gebers, 1996; Smith, 1996; Ryland, 1997; Ensminger, McCold and Webb, 1999).

9.11 Permits System

Annual contractual permits for iceberg utilisation could be granted by with conditions about environmental impacts. Ryland (1997) suggested that the granting of permits be linked to yearly reviews based on the impact assessments conducted in accordance with Annex I of the Protocol (Rothwell, 1992; Herr, 2000; Joyner, 2000). Icebergs operations would be forbidden when their influence and input on the ecosystems have negative effects. It would be possible to continue operations so long as freshwater input benefits exceed any adverse impacts on the ecosystems.

A system of quotas could be determined with precise quantities or volumes delivered per day under specific technical terms and conditions. As seen previously for the CEP, any assessment yielding more than a minor or transitory impact to any marine ecosystem would be denied (Ryland, 1997; O'Riordan, Cameron and Jordan, 2001). Building on the ideas of the Convention on the Conservation of Antarctic Marine Living Resources, the renewable iceberg resource would not fall below the amount which ensures the greatest net annual increment.

9.12 Iceberg Operating Committee

According to Schwerdtfeger[71] (1986 n.p.), iceberg operating would require the "vigorous support of one or more organisational sponsors in the political, commercial or development world; this role could be performed by a government planning agency responsible for long term water security, with access to adequate technical and financial resources" and decision-making abilities.

An administrative allocation regime which requires an authorisation, or a permit, from the Government before any public water can be used, seems to be the most appropriate for iceberg transportation. An Iceberg Operating Committee could combine the different obligations of the regimes concerning iceberg operations and establish specific rules for

[71] www.smec.com.au

iceberg transportation. The rules could address zoning to protect the most fragile areas, the obligation to cause no significant damage, to ensure that the required environmental protection measures and safety measures of operating are followed, the obligation to undertake regular environmental impact assessment, to ensure their renewability, to study the ecological elements related to icebergs, and the obligation to use the iceberg water within sustainable means. These rules could provide consistency between different legislation and support agreements for iceberg operating. Iceberg harvesting would respect all provisions currently administered by the ATS. The legal implications of iceberg ownership in the case of an accident could be addressed under the Law of the Sea to help resolve any political obstacles to iceberg transportation (Bishop, 1978; Ryland, 1997). For iceberg transportation projects, strict criteria for sustainability are needed to ensure the future of marine resources (de Sadeleer, 2002; Jabour and Weber, 2008[72]).

An Iceberg Committee could grant permits to the operators who would be required to comply with the guidelines for Antarctic icebergs use. Concerning their virtual ownership, the rule *res nullius cedit primo occupanti* (first occupant) in high seas as in the EEZ should be defined by a normative institutional and operational international authority that would be in charge of defining as well the environmental operating conditions. Therefore, the Iceberg Authority could establish the net annual increment of icebergs (currently about 800 km^3 usable) and issue permits with a total harvest always below that increment.

This institution would be able to deliver operating licenses, legal obligations for the operation as well as for the resource uses, and taxes securing the technical and economical feasibility of a transportation system. The institution would be able to ensure that the resource is well protected and managed using operating principles agreeing with the ATS and the CMB legal and moral models, a peaceful use, a conservation objective and operations that respects universal best interest (Burton, 1979[73], Dahl, 2004).

Collaboration between experts from different disciplines and fields and organisations, such as financing, shipping and trading companies might be required (Hussain, 1992; Cousteau and Charrier, 1992; Craven, 1993; Bederman, 1991; Duquin, 1995). Non Governmental Organisations could be involved to ensure that environmental interests will not be neglected and that the fragile environments of Antarctica remain preserved from the environmental degradation caused by iceberg operating (Barnes, 1985; Phillips, 1990). The NGOs have

[72] http://onlinelibrary.wiley.com/doi/10.1111/j.1467-9388.2008.00579.x/abstract
[73] http://www.jstor.org/pss/1072490

assumed a cooperative role within the ATS in terms of providing information, and helping to progress legitimate outcomes. For example, in 1990, the Antarctic and Southern Ocean Coalition (ASOC) secured observer status at the ATS meeting.

A Convention on icebergs could be validated by the UN, and a Permanent Court of International Justice capable of attracting territorial sovereignty could be created to ensure an efficient system of collective protection of the resource and sustainable development of its operating. The UN operates on the basis of consent (Beck, 1994; Brecher, 1994; Rothwell, 2000[74]; Lee, 2005) being a 'horizontal' organisation based on a "consensual system epitomised by the contract" (White, 2000 p. 291; Lee, 2005[75] p. 172). An Iceberg Committee may first evolve to a structure like a vertical governmental institution and then further to a more centralised model (Charney, 1993; Lister, 1996; Travis, 2002; Lee, 2005), or become a new independent administrative model which could overcome problems of inconsistent compliance with recommendations (Lentz, 1990; Lee, 2005). The new governance should reflect the new values of the modern world: harmony between economical objectives and the relationship between people and their environment with new challenging needs to be defined as values uses and units (Colding, 2001; de Sadeleer, 2002; Jabour Green and Haward, 2002[76]; Jabour and Bradshaw, 2004). Other types of world governance could be imagined (Joyner, 1998), which may take the form of a global regulator (Brecher, 1994; Nariman, 1997; Joyner, 1999), an external sovereignty with a single authority (Falk, 1991), one law and one system of justice, vested with mandatory powers as the International Court of Justice (Lee, 2005).

More specifically the Committee for Environmental Protection could take up the role of iceberg management within the context of the ATS. The Committee could be integrated to the annual Antarctic Treaty Consultative Meetings (ATCM) held by rotation in member states (Scully, 1991; Wolfrum, 1995; Scovazzi, 1996) and included in the Antarctic Treaty Secretariat in Buenos Aires, Argentina to support the annual ATCM and the meeting of the CEP (Ryland, 1997). In the interest of expanding the scope of the ATS, all parties would have to sign the Convention of the CEP in the manner detailed in the Agreed Measures for the Conservation of Antarctic Fauna and Flora and the ATS. All iceberg utilisation would be carried out exclusively within the framework of the Antarctic Treaty and adhere to sound

[74] http://www.ejil.org/pdfs/11/3/544.pdf, http://eprints.utas.edu.au/2661/19/17_Rothwell.pdf
[75] http://law.nus.edu.sg/sybil/downloads/articles/SJICL-2000-2/SJICL-2000-281.pdf, and www.gonzagajil.org/pdf/volume9/Lee/Lee.doc
[76] http://eprints.utas.edu.au/2661/26/Front_matter.pdf

scientific principles. In the case of Australia, the SCAR plays a role in this deliberation to assist CEP.

9.13 Conclusion

The objective of this chapter was to define the legal identity of icebergs and a legal frame for iceberg transportation. The main projects of iceberg transportation launched in the 1970s were suddenly dropped in the 1980s, which could explain the relatively rapid decline in legal attention. In this chapter relevant aspects of the ATS and marine legal regimes were examined to see how iceberg operating could be managed. Impact assessments are required by the Madrid Protocol. Particular attention has to be given to environmental impact assessment provisions. Of particular importance was the Annex I on environmental impact assessment under the Madrid Protocol - any operator will have to fulfil these obligations. Impacts are complex to define. Icebergs operating impacts can be chemical, thermal, optical, oceanographic (salinity, density, deposits), and climatic. With a specific compensation system, icebergs operating impacts could be minor or transitory. The chapter has raised important international and Australian legal dimensions that have a direct bearing on towing icebergs from the AAT to WA. While there is no specific Australian legislation or regulations that deal with iceberg transportation, the existing legal framework offers environmental impact assessment provisions under Australia's Antarctic Treaty Environmental Protection Act and the Environment Protection and Biodiversity Conservation Act (EPBC). New demands and possibilities for iceberg transportation between Antarctica and Australia raise new legal issues. Australia is a leading nation in the Commission for the Conservation of Antarctic Marine Living Resources and could play a substantial role in determining the legal status of iceberg transportation. The specific conditions for iceberg operating systems defined in this thesis are compatible with the different regimes of the ATS and the UNCLOS. However, a specific protocol for iceberg transportation to limit potential environmental damage could be elaborated. Several key issues must be studied to develop an efficient, safe means of iceberg harvest. They consist of:

- a bagging process to limit thermal/salinity/chemical gradients induced by iceberg transport operation. As regards the effects induced by the light, the sheltering and the potential instability, the harvesting of tabular icebergs by bags would use the natural behaviour of drifting icebergs. The effects would be close to the natural effects of icebergs drifting;

- a zoning system to limit the potential environmental damage induced by icebergs transportation. A geographical zoning for icebergs capture would be restricted to specific high seas zones. As regards the zoning of icebergs capture, the methodology defined by the International Ice Patrol could be used, minimising the dangers for navigation and operating with minimal ecological disturbance;
- resource planning would complete the zoning. Operation schedules are proposed in order to choose the optimal seasons for iceberg capture and to minimise the environmental damage and the hazard for technical operations. These studies must be updated regularly. Establishing a harvestable volume would limit damage to the Antarctic maritime climate and ecosystems. In such a framework, iceberg transportation would not affect the capacity of ice shelves to produce icebergs;
- a compensation system for replacement of the mineral elements contained in the harvested icebergs. It consists of artificially replacing the iron elements contained in icebergs and used in plankton blooming by a unique process, in order to reduce the potential ecological hazard.

Environmental impact assessments would help to allocate the resources and to plan operating processes in international and domestic context. Regular environmental impact assessments would help to establish that these guidelines are respected. These assessments should take into account thermal, chemical and physical measurements related to harvesting, transporting and supplying of the iceberg resource. In summary, with correct Environmental Impact assessments provisions, iceberg transportation from AAT to WA could occur under existing arrangements. Icebergs are a promising marine resource as their transportation would neither endanger the Antarctic region nor generate aggressive competition among intending users. However, the technologies involved must be carefully regulated to minimise the environmental impacts on wildlife, conservation and other public socio-cultural interest values (Schwerdtfeger, 1985). These guidelines concern precise zones for the operation of icebergs, identification of the harvestable iceberg resource, technical prescriptions, and prescriptions over micro and macro organisms as well as mineral elements of the related ecosystems. These legal guidelines for iceberg transportation could be a basis for the establishment of operating rights. Icebergs need legal distinction and identity, stated by a convention or a regime in order to create an international iceberg authority (such as a committee or a commission) ruling specific zones and protecting marine environmental resources. A legal authority would be able to define effective regulation tools, such as permits, charters or contracts (water rights) and management zones, to ensure reasonable access to the resource, determine the strategies for the development of a sustainable operating of the iceberg natural resources, generate rigorous impact assessments with proper ecological criteria, and regulate navigation issues, including liability of operators and their states for environmental damage. I propose the creation of a Committee and a protocol (which can determine answers to questions such as where should the water be operated, who could operate it, when, how much, and how). The legal structure of iceberg operating should be based on practical points of view as well as theoretical principles, as iceberg operating is still a new and developing practice. The goal is to develop environmental requirements and then a flexible means of transportation by bags on an industrial scale, such as the system presented in this thesis. The following chapter considers economic aspects of iceberg transportation systems.

Chapter 10 An Economic Analysis of Iceberg Transportation

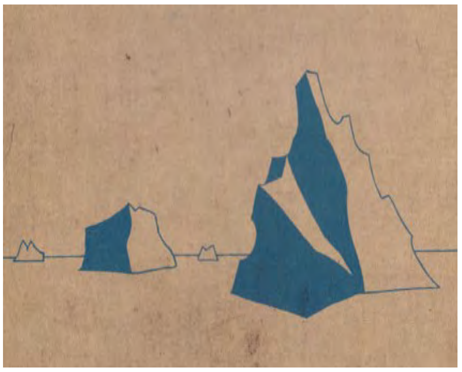

Figure 10.0a Icebergs (credit Gains and Bobri, 1964 book cover[1])

Figure 10.0b Icebergs (credit Gains and Bobri, 1964 p. 10)

The ideal transport mode would be
instantaneous, free, have an unlimited capacity and
always be available. It would render space obsolete.
This is obviously not the case. Space is a constraint
for the construction of transport networks.
Transportation appears to be an economic activity
different from others. It trades space with technology
time and thus money
(Translated from Merlin, 1992 p. 3
in Rodrigue 2009 n.p.[2])

[1]http://chrisashley.net/weblog/archives/cat_book_covers.html
[2]http://people.hofstra.edu/geotrans/eng/ch1en/conc1en/ch1c1en.html

Chapter 10 Economic Analyses of Iceberg Transportation

To understand the economic potential of iceberg transportation requires an investigation of the economics of water. Water uses and demands and the environmental needs determine the economic value of water. The economic costs of water depend on the amount of water available and the technological costs of water supply. Water costs and demands are in interaction (VTPI[3], 2005). According to Banister and Berechman (2001[4]):

> Economic transportation geography examines how space specialisations and values are influenced by the presence of transit networks. Analysis is based on the costs of movements, the construction and maintenance of transport modes and infrastructure, the evaluation of the transport demand by different sectors of activity and the performance of transport systems measured by economic criteria.

The objective of this chapter is to assess the economic costs and benefits associated with the transport of icebergs from the AAT to Perth in WA. Therefore this chapter will focus on the research of a case study for iceberg transportation costs based on the different technical elements of the sustainable system identified previously in this thesis. The objective is to estimate the cost of supplying iceberg water. It will be based on an evaluation of the cost of iceberg operations. Costs calculations for iceberg transportation are based on information about the costs of the investment including the operation and distribution of iceberg freshwater. According to Smakhtin *et al.*, (2001[5]) any attempt to estimate iceberg transportation costs would be approximate as iceberg operating techniques and infrastructures are not developed yet. According to Smakhtin *et al.*, (2001, p.18) costs will include the costs of:

> [I]ceberg detection and route tracking, transportation, operation and maintenance at destination ports, minimization of pollution losses…prevention of hazards to shipping… and construction and operation of a storage facility for the meltwater.

The main outcome is to investigate what are the realistic possibilities for an iceberg transportation project from the AAT to WA to be economically viable within the current water

[3] Victoria Transport Policy Institute
[4]http://www.sciencedirect.com/science?_ob=ArticleListURL&_method=list&_ArticleListID=1602931546&_sort=r&_st=13&view=c&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=b3002c3b1004b6929e1a11e3ba0da41e&searchtype=a
[5]http://www.waternet.co.za/we/docs/pete_unconventional_sources.pdf

market. This will help to determine a cost range of the resource that is transported and to estimate the benefits of the transportation system and compare it to the costs of other water transportation systems. Iceberg transportation can supply freshwater for different uses.

10.1 Space Specialisation and the Transit Process

Transportation, as an economic activity, seeks to minimise distance, time, effort, and cost, while seeking to maximise environmental benefits, and to develop optimal and efficient transport mode infrastructure, characteristics, operations and management, between locations (Rodrigue, 2009). Optimisation of the routes and spaces are based on minimising costs and maximising efficiencies. As a general rule, transportation costs vary according to the type of transportation modes. For example, road has a lower cost function for short distances up to 700 km, while rail is usually most cost effective between 700 km and 1,500 km, from which point maritime transportation becomes cheaper (Stopford, 1997; see also Figure 10.1).

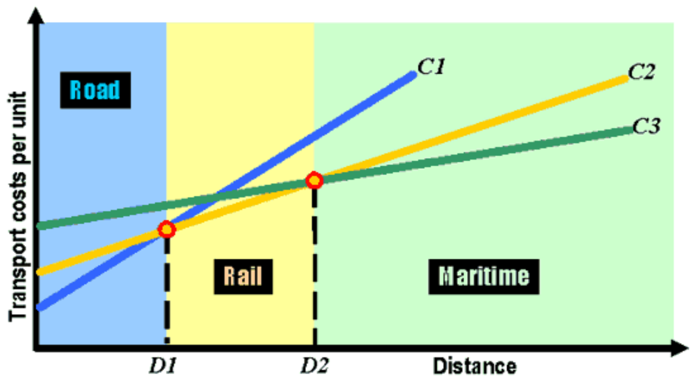

Figure 10.1 Modes of Transport and Associated Costs and Distances (credit Rodrigue *et al.*, 2009[6] n.p.)

Some transportation and supply services, despite being more expensive to build and operate, provide more services for an area and can be built for political reasons rather than for economic considerations (Roberts, 1999). For example, desalination plants cost more than other water supply systems, but are often built because they offer a reliable and efficient water supply. However, in general the cost of a transport service and its efficiency

[6]http://people.hofstra.edu/geotrans/eng/ch7en/conc7en/ch7c1en.html

determine the level of specialisation of sites. For pipelines, the cost to transport the water to a distant region limits its feasibility to a specific range (Page, 1977).

10.2 Space Values and Transit Networks

The value of space depends on the demand for products transported to this space, on the technological inputs required to transport these products and on the spatial division of production linked to the nature of the site and of the product and its scale of production (Rodrigue, 2009). To compare with other supplied destinations, the costs of the distance of transportation has to be compared with the demand for water transportation, which depends on the density and the opportunities of uses and the related potential benefits which can be obtained from this demand (Figure 10.2).

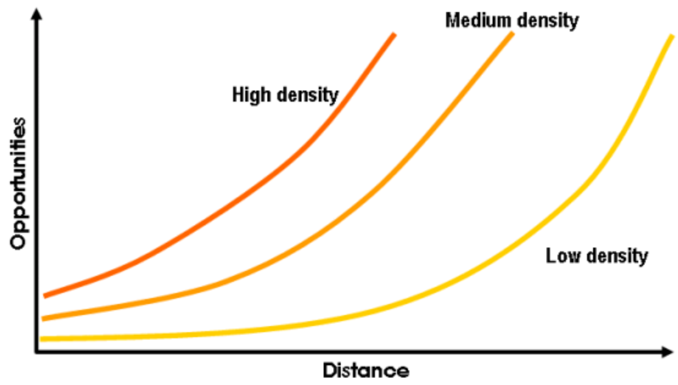

Figure 10.2 Relationships between Distance and Opportunities (credit Rodrigue *et al.*, 2009[7] n.p.)

The water transportation industry is traditionally characterised by an exponential relationship between distance and costs of transportation (credit Rodrigue *et al.*, 2009). In the case of traditional iceberg transportation systems, the larger the distance is, the less water demand affects the cost benefit results. Cost and distance minimising are more important than the nature of the demand and its timing. For the iceberg transportation system from Antarctica to WA the distance is minimal as WA is one of the closest locations to the operating site and the transport technologies and the spatial division of production linked to the nature of the site of production are optimal in terms of transportation costs related to fossil fuels consumption.

[7]http://people.hofstra.edu/geotrans/eng/ch2en/conc2en/ch2c4en.html

The characteristics of the sites represent fundamental obstacles for the transportation network by determining a substantial part of accessibility costs. The accessibility costs are composed of costs of infrastructure building, environmental requirements, physical and climatic constraints. The transportation scope, productivity, safety, costs and choice of modes, are all highly dependent on the sites where transportation activities are implemented (Rodrigue *et al.*, 2009).

Transportation systems are often assembled on the most functional, practical and profitable axes and the selection of the distribution sites are made according to their accessibility (Rodrigue *et al.*, 2009).

Iceberg transportation projects from Antarctica to Saudi Arabia, or from the Arctic to Africa or North America, face the difficulty of overcoming shallow seas (Hult and Ostrander, 1973; Weeks and Campbell, 1973; Victor, 1978; Sobinger, 1985). Waterbag technology would help to overcome the physical and environmental obstacles related to depth at the destination location. The transportation of icebergs would be limited by the depth of destination locations whereas waterbags can be delivered to more shallow locations. For the iceberg transportation project proposed in Chapter 7, the bagging technology would enable water to be delivered to a large number of locations. The sites from which icebergs would be harvested are located in the high seas, in a sector where the currents are flowing toward WA, meaning that it would be possible to operate and transport icebergs to WA with a maximal use of currents and winds. The route from the AAT to WA, and the characteristics of the operating location would provide good accessibility with this transportation system.

Geographical impacts of the geophysical environment of transportation activities depend on distance and accessibility, affecting directly the cost of transportation. The friction of distance is the cost associated with a longer fraction of transportation, and is estimated as cost, length, time or energy used. The friction of distance varies between modes and geographical transportation environments. Some regions have higher transport costs and less access to transportation technology.

The iceberg transportation system proposed in this thesis would be highly dependent on the running distance. The system would therefore be run on short routes and would use mainly non-fossil fuels. The costs and efficiencies of infrastructure operating and transportation are minimised at the expense of the duration factor; a slower transportation system is generally cheaper.

WA is ideally located to be supplied with icebergs. WA is an ideal destination and launching point for iceberg operations because of its water needs and the technical facilities it offers. Freshwater iceberg resources could represent annually up to 1,300 km^3. (Hult and Ostrander, 1973[8]). A single iceberg of 3 km^3 (5 km by 2 km by 300 m) could supply the amount of freshwater consumed by Australians in one year. Harvesting a 0.1 km^3 iceberg (3 km long, 300 m large and 100 m high) every year could represent 25% of Perth's annual water consumption (3 km^3 for 30 years). The city of Perth represents a regional attraction zone with a high convergence of economic activities, and specifically with high water demands.

The socioeconomic environment of Perth is particularly favourable for water transportation projects. Furthermore, 19 km from Perth is Freemantle the largest and busiest general cargo port in WA. Fremantle Port operates the Kwinana Bulk Jetty and Kwinana Bulk Terminal[9]. The Kwinana Outer Harbour is an important bulk cargo harbour in Australia, handling mineral, petroleum and bulk chemical freight[10]. A railway links the North Quay in Fremantle and the Kwinana Quay to the regional and national railway networks. The outer harbour is deep which previously led this location to be considered for iceberg transportation (Rowden-Rich, 1986).

Transportation transforms locations, making some places more valuable than others, and some transportation modes as more appropriate and more cost effective. The relationship between transportation's transformation of locations and the different types of transportation modes is highly influenced by the costs of the transportation services.

In determining the spatial structure of a transportation network, decisions are taken in order to minimise transportation costs and maximise the accessibility of the resource. Some locations are more accessible than others. Moreover, according to Rodrigue (2009) concerning the distribution sites: "the development of a location reflects the cumulative relationships between transport infrastructure, economic activities and the environment". The production of resources relies on accessibility to international freight distribution for exportation and importation. According to Rodrigue (2009[11] n.p.):

[8]http://www.rand.org/pubs/reports/2008/R1255.pdf
[9]www.fremantleports.com.au
[10]www.fremantleports.com.au
[11]http://people.hofstra.edu/geotrans/eng/ch2en/conc2en/ch2c4en.html

> Since accessibility is dominantly the outcome of transportation activities, namely the capacity of infrastructure to support mobility, it presents the most significant influence of transportation on location.

The attributes of the end-destination site and the level of accessibility are therefore suitable for iceberg transportation. It is important to estimate the outcome of the transportation of iceberg water as a large input of freshwater in the socio-environmental water system at destination sites to evaluate the feasibility of the project. Iceberg transportation could become a factor driving the spatial organisation of socioeconomic activities, manufacturing and services creating structural change caused by the expansion of new growing industries which can benefit from a large input of freshwater (such as agricultural activities). Perth is an exceptional location in relation to Antarctica and has the requisite harbour infrastructures to act as a destination site for icebergs. These qualities mean that iceberg transportation costs could be minimised by using it as the end-destination for transported icebergs and could provide benefits depending on the costs of the transportation modes.

Between transportation costs, efficiency of the transportation and the value of the goods a compromise can be found, where the route selected tries to satisfy all the criteria, with low costs, high efficiency and high demand routes (Figure 10.3).

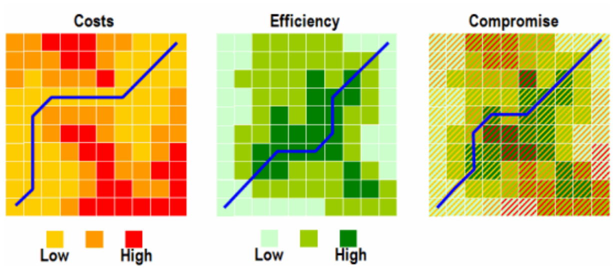

Figure 10.3 Compromise between Cost Minimisation and Efficiency Maximisation (credit Rodrigue *et al.*, 2009[12] n.p.)

In contrast to the system advanced in Chapter 7, the costs associated with shipping icebergs would be dominated by fossil fuel costs, with lower efficiencies in terms of energy consumption and environment protection. The energy consumption would depend on the time of transportation, so a shipping project would try to use the quickest route. The difference in distance with the route following the currents would not be substantial. This

[12]http://people.hofstra.edu/geotrans/eng/ch2en/meth2en/routecomp.html

route corresponds closely to the shortest route between Kerguelen Island and WA. An iceberg transportation system that used non-fossil fuels would minimise the transport infrastructures required and the environmental impacts from operating such a system. In the next section of this chapter the cost components of an iceberg transportation system using non-fossil fuels is analysed in detail.

10.3 Transportation Costs

Transportation costs are composed of fixed costs (including capital costs, infrastructure and equipment costs) and variable operating costs (which include the costs of operation, energy, maintenance, technological development, staff, trade, and insurance).

Capital costs are associated with transportation infrastructures and physical assets. Maintenance costs include a part of capital investments as physical assets values decrease over time. The infrastructure determines the efficiency and capacity of transport modes (Rodrigue, 2009). In particular, for the iceberg transportation project considered in this thesis, terminal costs would be comprise loading and unloading activities at the delivery sites (Spragg, 2001).

Operating costs vary depending on freight weight and volume, product type, and mode of transportation (Rodrigue, 2009). Each type of product has different characteristics which are cost sensitive. Depending on its characteristics (such as the weights transported), each product will require a specific consumption of labour and fuel**.** Each type of product requires different sorts of packaging, handling and storage facilities. Each mode has specific operational conditions and related capacities. Economies of scale imply that quantities transported are inversely correlated to unit costs. Concerning transportation of primary resources such as energy resources (coal, oil), grains, minerals, and water substantial economies often result from large scale of operating.

The transportation of a barrel of oil over 4,000 km could cost AUD1 on a 150,000 t tanker ship and AUD3 on a 50,000 t tanker (Rodrigue, 2009). Modes are also influenced by the transport time. Transport time affects the accessibility of a product and the relation between the accessibility of a product and its demand defines the level of servicing, tradability and pricing of the product (Rodrigue, 2009). Transportation costs directly determine transportation frequencies and ranges (Rodrigue, 2009).

The maintenance costs of transportation systems depend on the state of the technologies employed and on the operating conditions (Rodrigue, 2009).

Insurance costs often are generally related to the value and the weights of the transported product and to the environmental risks of transportation (Rodrigue, 2009). According to Rodrigue (2009 n.p.): "[T]he Costs Insurance Freight (CIF) is a transport rate that considers the price of the good, insurance costs and transport costs".

Energy costs are very sensitive to energy prices. Trade costs consist of "gathering information, negotiating, and enforcing contracts and transactions" (Rodrigue, 2009[13] n.p.). Transaction costs, including legal costs and insurance can be significant for international movements as issues related to currency exchange as well as custom duties have to be considered. The transportation regulation of trade happens in a complex and competitive environment. The costs of regulations on prices, operations, working conditions and safety, result in institutional and trading concentration of transportation. Arden Colette and Almas (2003[14], p. 750) noted:

> Water marketing may be defined as the selling of excess water supply from one use to individuals or institutions for uses where there is excess demand. The trade transactions relevant to water marketing can occur either through the sale of water right permit or through the sale of water by means of a water supply contract.

The processes of legislation, litigation and negotiation for water transportation activities are common and cover other costs such as environmental ones. Costs analyses of the materials used in the technologies of the iceberg transportation system identified in Chapter 7 studied will be detailed now.

10.4 Project Cost Analysis

After having established in Chapter 7 the specific considerations within which an iceberg transportation system using non-fossil fuels could be technically feasible, the likely costs of such a proposal can now be estimated in detail. Iceberg freshwater transportation system costs can be estimated on the basis of the actual average cost of each of its components. The costs of each component are dependent on the scale of the transportation system within

[13] http://people.hofstra.edu/geotrans/eng/ch7en/conc7en/ch7c3en.html
[14] http://www.crcnetbase.com/doi/abs/10.1201/NOE0849396274.ch179

which they operate. For the iceberg transportation system model based on kites and currents described in this thesis, several costs are estimated for different experimental and operational scales. The capital and the infrastructure consists of a tug ship with the materials for the operation, a foam belt, an iceberg bag, nets, a collar, waterbags, kites and other spare gear for towing and harnessing operations.

Including labour and material, the purchase cost of powerful tug boats varies between AUD1.6 million and AUD20 million[15]. Shipping costs decrease over time and use especially for primary goods and non-manufactured goods like bulk freshwater (Radelet and Sachs, 1998[16] p. 11). In order to estimate the likely operating costs of the iceberg transportation system, the ship costs were based on costs for a return trip and for iceberg preliminary operations with minimal fuel usage. The petroleum and crew costs are detailed in the sailing costs. These costs cover both investments and operational costs (Figure 10.4).

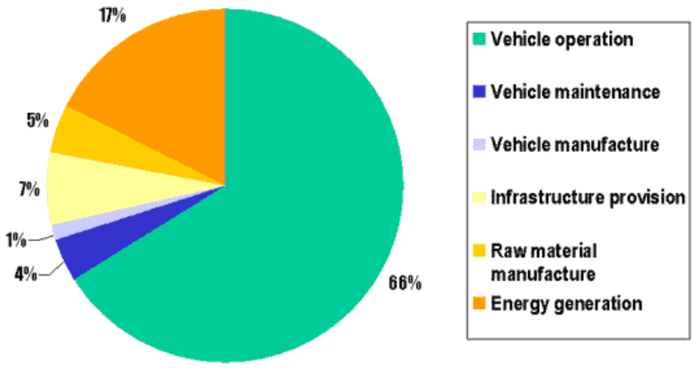

Figure 10.4 Energy Used by the Transport System (credit Tolley and Turton 1995, cited in Rodrigue 2009[17] n.p.)

The prices for the iceberg bag, the wrapping collar and the waterbags are based on the price of plastic membrane resin. For example, a 50,000 t reinforced membrane bag (4 mm thick) requires 20 t of plastic membrane. Plastic membrane costs AUD1,500/t. But with economies of scale the prices can decrease to AUD1,000/t for projects requiring over 20,000t, AUD700/t for projects requiring over 120,000 t and even AUD320/t for projects requiring over 1 million t (Plastic Technology, 2010). The labour costs are sensitive to scale savings but can be estimated at less than 10% (M.Holland, Plastic Exchange, 2010).

15 www.maritimesales.com
16 http://admin.earth.columbia.edu/sitefiles/file/about/director/pubs/shipcost.pdf
17 http://www.people.hofstra.edu/geotrans/eng/ch9en/conc9en/ch9c1en.html

For the kite systems, costs can decrease with scale. However, a large capacity kite will cost between AUD500,000 for a 600 m^2 kite and AUD2 million for a 5,000 m^2 kite (Kiteship, 2010[18]). The costs of average size (1,000 m^2) kites produced in large series would be roughly about AUD150,000 per unit (Skysails, 2010[19]; Kiteship, 2010). This system would minimise operating costs as it is a semi-automatic system. These prices include labour costs to make them.

Vehicle and terminal costs are likely to be significant in iceberg transportation projects. The type of transportation system and the cost of its technologies determine the capacity of the system (Kuby and Reid, 1992). The transportation sector tends to have high entry costs and requires high capital investments. The cost of transportation can account for the majority of the total cost of a product (Rodrigue, 2009). Even though entry costs can be high they could be covered by the fact that transportation demand provides short term returns.

However, physical conditions of transportation limit technological cost predictions. This principle is particularly relevant for iceberg transportation because the materials and technologies required have not been designed and tested yet and because the transportation process would be undertaken in a region where extreme climatic and maritime conditions occur regularly. The calculation of the technological cost variability can be estimated by applying a specific coefficient which could evaluate the range of possible variations in costs (Yeo, 1991). For an iceberg transportation system using non-fossil fuels, the uncertainties about the system design and materials and the associated technological costs variability can affect the total costs (Shittu, 2009[20]). These impacts vary and depend on the types of technological elements involved, but for maritime transportation an average coefficient would be approximately 1.25 (Hummels, 2007; Mulligan, 2008). Assuming that reasonable variations of the estimations can occur, a technological coefficient of 1.28 could be assigned to the costs of iceberg transportation systems.

Operating costs can grow in non-linear ways with capacity and distance as they also include the costs of returning the bags and material empty to their Southern Ocean resource extraction locations. Operating costs are estimated on the basis of person hours per tonne of goods and labour rate per hour (Watson, 2003). For sailing and operations activities it is

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[18] http://www.kiteship.com/
[19] http://www.skysails.info/index.php?id=472&L=2
[20] http://scholarworks.umass.edu/open_access_dissertations/51/

estimated that a crew of 10 persons could operate the iceberg for 10 years (and cost more than AUD3 million).

The petroleum-fuelled operating transportation system and associated energy costs increase linearly and proportionally with distance (Rodrigue, 2009). The consumption of fuel relates directly to the distance travelled. For operating costs, depending on the stages of the experiment, or the operational phases, the costs evolve according to the material and techniques involved. Iceberg transportation systems with waterbags based on renewable energies, such as kites and ocean currents, would have reduced transportation costs. The fact that the system studied in Chapter 7 is based on currents and winds energies is the main element that makes the project feasible.

In the proposal outlined in Chapter 7, icebergs would therefore be caught 2,000 km away from the Amery Ice Shelf (the Amery Ice Shelf is 4,200 km from Perth). In Chapter 3 it was established that the combined effect of the Circumpolar Current and Antarctic winds could provide transportation for icebergs and the water collected from them for up to some 2,000 km of the total journey to the Australian coast. The energy consumption can be calculated as the mass (M) times the Distance (d) times the efficiency or the force in pounds times the distance. For the calculations we used both the estimations of force requirements of Hult and Ostrander (1973), Mauviel (1980), Sobinger (1985) and the C-CORE (2007) as well as the towing efficiency figures.

For instance, the return trip to transport a 25 million t of two 20,000 t boats carrying the iceberg bag over 1,700 km would require a consumption of: 2 x 20,000 x 1,700,000 x 0,7= 60 GJ. An average consumption of 1 t of fuel corresponds to 44,000 MJ. More than 2 t of fuel would be needed for these trips.

The 2km/h launching of the iceberg of 20 km would represent 20,000 x 25,000,000 x 0.2 = 100 GJ. More than 4 t of fuel would be needed for this operation.

To commence transportation using currents and winds, bagged icebergs would be first steered by kites at 0.7km/h on 400 km and melted instead of being towed. There is then no significant fossil fuel propulsion required for the bagged iceberg steering. The resulting savings would correspond to 400,000 x 25,000,000 x 0.2= 2,000 GJ. More than 80 t of fuel would be needed for this operation.

The waterbag convoy of 1,000,000 t (50 bags of 20,000 t) would then launched over 40 km in the Circumpolar Current. Twenty five convoys would be required to transport over 1,400 km all the iceberg water at 2km/h and consume and energy of 40,000 x 1,000,000 x 0,75 x 25 = 900 GJ. Less than 40 t of fuel would be needed for this operation.

There is then no significant fossil fuel propulsion required for the convoy until it gets to 1,400km within 100 km of Perth. The resulting savings of bag steering at 2km/h would correspond to an energy consumption of 1,400,000 x 1,000,000 x 0,75 x 25 = 1,200 = 5,000 GJ. Less than 200 t of fuel would be needed for this operation

A tug would be sent to deliver the convoy. The delivery towing distance is 100 km. For the first trip the energy consumption would be around 20,000 x 100,000 x 25 = 50 GJ. For the return towing trip the energy consumption would correspond to 1,000,000 x 100,000 x 25 = 2,500 GJ. Less than 100 t of fuel would be needed over two days.

Table 10.1 provides details on the energy consumption of the Iceberg Transportation Project for a large tabular iceberg (2 billion t).

Table 10.1 Energy Consumption of the Iceberg Transportation Project of Chapter 7

Transportation Steps	**Transported device**	**Transportation Distance (km)**	**Transportation Energy (GJ)**	**Fuel Use (t)**
From original Shelf to capturing point	2.5 x 10^7 Iceberg drifting	2,200	0	0
From Destination to Capturing Point	tug boat with materials, 20,000 t Return of the tug boat	2,000 km 2	60	2
From Capturing Point to Melting Point	Iceberg launching	20 km towing 400 km drifting	100 2,000 saved	4
From Melting Point to Delivery Point	25 Trains of 50 bags of 20,000 t launching	20 km towing 1,400 km drifting	900 5,000 saved	30
At Melting Point	Train operation	>100	80	>1,8
From Delivery Point to Destination and first way	Train towing	100	2,500	110
Total	20,000	4,200	3,600	150
Pure towing	2.5 x 10^7 Iceberg	2,000	20,000	400

Table 10.2 sums up the energy and petrol consumption of the project of this thesis depending on scales.

Table 10.2 Energy and Petrol Consumption of Iceberg Transportation Projects Depending on Scales.

Iceberg scales	2.5 x 10^7 Iceberg drifting Consumption GJ	2.5 x 10^7 Iceberg drifting Fuel Use (t)	2.5 x 10^8 Iceberg drifting Consumption GJ	2.5 x 10^8 Iceberg drifting Fuel Use (t)	2.5 x 10^9 Iceberg drifting Consumption GJ	2.5 x 10^9 Iceberg drifting Fuel Use (t)
Bags towing Kite currents drifting	3,600	150	35,000	1,500	3,150,000	15,000
Tow and bags	10,500	330	72,500	2,000	6,500,000	33,000
Pure towing	20,000	650	150,000	4,800	13,000,000	65,000

This table shows that the iceberg transportation project based on bags, kites and currents uses, would consume two to three times less petrol than the towing of a bagged iceberg and five times less than the raw towing of the iceberg. For example, the energy requirement for a 200 million t iceberg corresponds to the consumption of about 1,5000 t of diesel fuel. Diesel fuel oil costs about AUD0.80/l thus, the cost for diesel fuel is AUD1,2 million per delivery. Pure towing petrol costs would be five at least five times higher.

Terminal (loading or unloading), specific institutional legal and trade costs would increase overall transportation costs. The investment costs of the distribution facilities and the operating costs of maintenance are generally structural and depend on the capacity and the scale and not on distance.

In the water transportation industry, pollution and wastes represent an external negative cost. Iceberg transportation systems based on renewable energies with waterbags and kites and currents would reduce emissions and associated transportation costs. Fuel emissions related to production of the bags, boats and infrastructure could be reduced by the use of environmental friendly materials and technologies. For a large scale iceberg transportation project requiring the use of 0.13 million t of plastics and 10,000 t of iron, CO_2 emissions could be reduced by 50% from around 1 million t to 0.5 million t (Kuckshinrichs *et al.*, 2007; Pusch, 2009; Worldwatch Institute, 2009). This represents 20,000 t of CO_2.

Diesel fuel emits 2.7 kg/l of CO_2. Thus, the iceberg transportation of the project described in chapter 7 involves a global emission of 43,000 t. The emissions for the delivery of the material for the operations of the iceberg represent 6,000 t of CO_2, 3,000 t of CO_2 for the bags launching operations and 6,000 t of CO_2 of the delivery towing operations. This represents 40,000 t of CO_2, for an iceberg of two billion t. With the material and the expedition costs it arrives at 60,000 t which is around 0.00003 l of CO_2/t of water.

In the recent discussions in Australia about the price of CO_2/t it was estimated around AUD32/t (Ford *et al.*, 2009). Therefore, a large scale project could cost AUD2 million.

The cost of the compensation program for mineral elements contained in the iceberg would vary according to the scales of the size of iceberg operated. Mineral elements would be released to compensate for the amounts of mineral elements that transported icebergs would have contributed to the environment. Icebergs melt naturally in the sea. These elements could be obtained from the iceberg melt water contained in the bag. The environmental costs of iceberg operations would correspond mainly to the costs of the transportation and the release processes of these elements. It is estimated that 0.5‰ of the iceberg water has to be released in the form of mineral elements to compensate:

- at a small scale - for a 3 million t iceberg - it is estimated that less than 50 t of mineral elements should be released (AUD40,000 - AUD0.4 million) for environmental purposes;
- at a medium scale - for a 25 million t iceberg - it is estimated that about 300 t of mineral elements should be released (AUD300,000 - AUD3 million) for environmental purposes;
- at a large scale - for a 200 million t iceberg - it is estimated that 2,000 t of elements should be released (AUD2 million - AUD25 million);
- for a 2 billion t iceberg, 20,000 t of elements should be released (AUD20 million - AUD170 million).

The insurance costs and the trading costs of transportation depend generally more on contractual agreements. These costs decrease when the scales of transportation increase. In shipping, insurance costs are usually in the 1 to 2% range (Hult and Ostrander, 1978; Radelet and Sachs, 1998).

The maintenance costs depend on the materials and technologies involved in the transportation system. Iceberg bag and installations could last from 10 to 15 years based on the material lasting times. The waterbags could last around seven to eight years. The lifetime of these entities could be improved with new materials and with on-going advances in maintenance processes. Table 10.3 and Table 10.4 provide cost estimates of iceberg transportation systems depending on their different stages. These costs are adjusted by economies of scale, depreciation, interest rates and with discounting margins (Hummels, 2007).

Table 10.3 Costs Measurements for a Small Iceberg Transportation Projects

Operating elements	**Stage 0 1 m^3: Size in m^3**	**Stage 0: Estimated cost in AUD**	**Stage 1 1,000 m^3: Size in m^3**	**Stage 1: Estimated cost in AUD**	**Stage 2 50,000 m^3: Size in m^3**	**Stage 2: Estimated cost in AUD**
Boat hiring	-	-	-	24,000	-	160,000
Iceberg foam net and bag	1	800	1,000	8,000	50,000	32,000
Wrapping collar and waterbag model	1	800	1,000	8,000	50,000	32,000
Kite system	-	-	-	-	360	24,000
Iceberg sample, detection and analysis	-	320	-	16,000	-	16,000
Transportation operation, sailing, crew, facilities	-	6,400	-	8,000	-	160,000
Maintenance costs	-	-	-	-	-	24,000
Insurance and legal costs	-	-	-	-	-	24,000
Trading fees	-	-	-	-	-	32,000
Environmental protocol costs (buoys and CO_2)	-	-	-	-	-	10,000
Total value	-	3,2	-	3,200	-	160,000
Total costs	-	8,500	-	64,000	-	540,000

Based on the above calculations, the experimental stages of the iceberg transportation proposal would not be profitable.

- at a pool scale, a 1m^3, 1m long 1m wide 1m deep iceberg with a 0.3 kg empty collar, a 2 kg empty iceberg bag, a 2 kg empty waterbag model. The iceberg could melt in the collar. The maximum collar expandable capacity would be around 1,000 kg;
- at a small in-situ experimental scale, a 20 m long 10 m wide 5 m deep iceberg (1,000 m^3) would be used with a boat with 1 t of materials, a 10 kg empty iceberg bag model, a 10 kg empty collar model of an expandable capacity of 1,000 t, and a waterbag model of 1t towed by the boat simulating the current/kite traction;
- at an average in-situ experimental stage, a 60 m long 40 m large 20 m deep iceberg (50.000 t), would be used with a boat with 50 t of materials, a 20 t empty iceberg bag, a 20 t

empty collar waterbag of an expandable capacity of 50.000 t, a 10 t kite and about 30 t of other gear.

Table 10.4 Costs Measurements for a Large Iceberg Transportation Projects

Operating elements over 10 years	**Stage 3 (for 2 years) 3 million m³: Size in m³**	**Stage 3: cost in AUD**	**Stage 4 25 million m³: Size in m³**	**Stage 4: cost in AUD**	**Stage 5 200 million m³: Size in m³**	**Stage 5: cost in AUD**	**Stage 6 2,000 million m³: Size in m³**	**Stage 6: cost in AUD**
Boat	-	0.8 million	-	5 million	-	40 million	-	250 million
Iceberg foam net and bag	3 million	2.1 million * (1,200AUD/t)	25 million*	9 million * (640AUD/t)	200 million	30 million * (320AUD/t)	2,000 million	210 million* (250AUD/t)
Wrapping collar	1.5 million	1.5 million * (1,600AUD/t)	3 million	6 million * (1,000AUD/t)	20 million	7 million * (640AUD/t)	200 million	28 million * (300AUD/t)
Waterbag	150 waterbags of 20,000	1.5 million * (1,600AUD/t)	120 waterbags of 50,000	3.5 million * (1,200AUD/t)	200 bag 50,000	5 million * (860AUD/t)	2,000 bag 50,000m³	15 million * (320AUD/t)
Kite system	2 kite systems 50m by 10m	1.5 million *	20 kite systems	8.5 million	50 kite systems	15 million	100 kite systems	25 million
Iceberg sample detection and analysis	-	160,000	-	780,000	-	5 million	-	30 million
Operation, sailing, tools, crew, facilities & expertise	-	1 million	-	8 million	-	55 million	-	350 million
Maintenance costs	-	480,000	-	4 million	-	30 million	-	200 million
Insurance and legal costs	-	320,000	-	3 million	-	25 million	-	200 million
Trading fees	-	150,000	-	2 million	-	20 million	-	150 million
Environmental protocol costs (buoys and CO_2)	-	0.4 million	-	3 million		27 million		180 million
Total costs Maximal costs	-	9.5 million 13 million**	-	50 million 70 million**	-	240 million 350 million**	-	1.7 billion 2,2 billion**
Total value	-	6 million	-	50 million	-	400 million	-	4 billion

*Capital cost include an interest rate of 5%/year and a **capital depreciation rate of 30% based on the average of large shipping projects 2000-2010 (Stopford, UNCATD 2008 n.p.). Combined it corresponds to a 3% interest rate.

Operational stage cost calculations are based on projects of icebergs being transported from Antarctica to Perth, WA. At a small real scale, a 3 million t, 300 m long, 200 m wide, 50 m deep iceberg could be operated, with a boat. The boat would have a capacity of 3,000 t of materials, a 1,200 t empty iceberg bag, a 600 t empty collar, 150 waterbags (empty weight of 8t each, so 1,200 t in total and a 20,000 t capacity), four 10 t kites and 100 t of other gear (helicopter, safety gear). The iceberg could melt in the collar (max capacity of 3 million t). A train comprising 150 iceberg waterbags could operate one return trip per year. Stage 3 would also not be profitable.

At a medium real scale, a 25 million t, 500 m long, 500 m wide, 100 m deep iceberg could be operated over 2.5 years, with a boat with a 20,000 t loading capacity, a 10,000 t empty iceberg bag, a 4,000 t empty collar, 120 20 t empty waterbags (2,400 t), 20 10 t kites and about 500 t of gear (helicopter, safety gear). The iceberg could melt in the collar providing an average rate around 6 million t of freshwater/year. The maximum collar expandable capacity could be around 6 million t and could be able to sustain the variations of melt for 12 months. One train of 120 bags of 50,000 t could operate two return trips/year, for a total capacity of 12 million t/year. With four trips over two years all freshwater contained in the iceberg would be collected. For a 25 million t iceberg, it is estimated that about 300 t of mineral elements should be released (AUD5 million) for environmental purposes. Stage 4 would be profitable.

At a large scale, a 2 km long, 1 km wide, 0.1 km deep iceberg (weight of 200 million t) could be operated over 10 years, with a boat with a loading capacity of 45,000 t of materials, a 100,000 t empty iceberg bag, a 10,000 t empty collar, 200 20 t empty waterbags (4,000 t), 50 10t kites (500 t) and about 500 t of gear (including a helicopter and safety gear). The iceberg would melt in the collar at an average rate, supplying around 20 million t/year of freshwater, or 1.6 million t/month. The expandable capacity of the collar could be around 20 million t so as to be able to sustain variations in the iceberg melt rate over a year. Two trains of 100 bags of 50,000 t could operate 2 return trips/year, for a total capacity of 20 million t/year. For a 200 million t iceberg, it is estimated that 2,000 t of elements should be released (at a cost of AUD27 million). The total infrastructure cost of the proposal could be around AUD20million with loading structures or floating cranes as well as a barge or a coastal trader. Stage 5 would be profitable.

At the maximal stage, a giant 5 km long, 4 km wide, and 0.1 km deep iceberg (2 billion t) could be operated over 10 years, with a supertug (1,000,000 t towing capacity), 800,000 t empty iceberg bag, a 80,000 t empty collar, 2,000 20 t empty waterbags (40,000 t), 100 10 t kites (1,000 t) and about 5,000 t of gear (helicopter, safety gear). The iceberg could melt in the collar with an average rate around 200 million t of freshwater per year. Twenty trains of 100 bags of 50,000 t operate two return trips/year, and a total capacity of 2,000 bags - 200 million t/year. For a 2 billion t iceberg, 50,000t of elements should be released (AUD160 million). The total infrastructure cost of the proposal would be around AUD50 million for Stage 6. Loading structures or floating cranes could be used as well as a barge or a coastal trader. This stage would be profitable.

10.5 Evaluation of the Transport Demand

Transportation costs are the costs of access, the costs of offering transportation services. The costs of transportation are different from transportation demand. The demand for goods to be transported corresponds to the needs for the goods transported, which correspond to specific values and uses. The demand determines a substantial part of the price of transportation (Rodrigue, 2009). Transportation demand and profit are difficult to distinguish. Transportation profits are hard to evaluate, because of their broad and widespread nature. The profit can be the profit of the provider or the profit of the society, even if this latter profit is often associated with the level of service provided and therefore with the demand. The profit of the provider represents generally the main part of the profit, is easier to evaluate and is the profit which is traditionally studied in costs benefits analysis. However the profit of the society should not be underestimated. Transportation profits and demands are in this sense, the result of political decisions: transportation profits can be shared by the society. They include technical and social factors, such as time savings or increased capacity, safety and quality of good long term effects, environmental and social factors (Rodrigue, 2009).

The demands and profits that might stem from an iceberg transportation project are numerous. As a freshwater supply resource, icebergs could contribute to the economic development of the destination country. Iceberg water is a high quality freshwater resource. Iceberg water could also be operated for health, safety and drinking purposes, for its physical chemical and thermal qualities (Iceberg water contains less than 100 mg/l of total dissolved solid (TDS) while safe drinking water standard for potable supplies is 500 mg/l. (ProvidIce, 2011[21]). Iceberg water as a new freshwater input in the land water system could reduce ecological damage on ecosystems and societies and be used for goods and services, food

[21] http://providice.com/acc-1.html

supply, waste purification, habitats, natural landscapes, and ecosystem protection. In terms of quantity and quality, iceberg freshwater supply potentially represents a rational, sustainable and economically efficient resource supply system. In this view iceberg transportation open socio cultural and economical perspectives through a new large input of freshwater in the destination water cycle systems (Table 10.5).

Table 10.5 Value and Uses of Freshwater

Value	Climatic	Ecological	Biological	Industrial	Recreational
Uses	Universal	Environmental	Health, safety drinking, irrigation, cleaning, cooling	Hydroelectric power	Aesthetics
Properties	Physical, chemical, thermal	Physical, chemical, thermal	Physical, chemical, thermal	Physical, chemical, thermal	Physical, chemical, thermal, social
Access	CO_2 absorption + storage in oceans	Living organisms	Living organisms	Human societies	Human societies
Quality	Variable	Variable	Variable	Variable	Variable
Quantity	Large	Large	Small	Large	Large
Timing	Short and long	Short and long	Short and long	Short and long	Short and long
Supply resource	All	Groundwater, lakes seas	Seas, groundwater, lakes, icebergs	All	All

Australia’s need for high quality water corresponds to high drinking water standards (NWC, 2007[22]). In Perth, drinking water demands are estimated to be around 6 km^3 over 30 years, which corresponds to the amount of water that could be supplied by the large scale iceberg project.

10.6 Price

Transport supply and demand are interrelated. Transport demand varies within different regions and at different times (Hummels, 2007). By contrast, transport supply is more stable. The price of transport is a function of the offer of the transport servicing company, comprising the costs of the service and a profit. Other elements affecting demand, including technical, political, commercial and institutional elements, can affect levels of servicing and represent a significant part of the price (Garnaut Climate Change Review, 2008[23]). Water

[22] http://www.water.gov.au/WaterUse/index.aspx?Menu=Level1_5
[23] http://www.garnautreview.org.au/pdf/Garnaut_Chapter21.pdf

supply costs consist of fixed accessibility costs that depend on capital costs and staff costs and variable costs (Anderson and Landry, 2001[24]). The demand for water is also determined by other factors such as cultural, ecological or commercial uses. The price of water depends on its accessibility and what it might be used for. When transportation offer is superior to transportation demand, transfer and transportation durations are more efficient and reliable as infrastructures are already well developed and prices are decreasing. When transport demand surpasses supply for a long period, there are higher levels of unpredictability and prices increase. The demand for water is generally higher in industrialised countries. These countries have also higher environmental demands. Prices can be estimated in volumes, or by uses and they can be variable or fixed. The emergence of a new transportation system is uncommon and relies on technological breakthroughs (Tolley and Turton 1995, cited in Rodrigue 2009[25] n.p.). Transportation operations with high technology entry costs can decrease their costs by operating on smaller distances or at lower speed and energy consumptions levels (Hummels, 2007[26]).

The interactions between water values and uses, and costs of demand and offer, imply that water pricing is difficult to evaluate. Water pricing can affect water use efficiency and cost at both the individual and social levels. In more economically developed countries (MEDC), water prices are often stable. They differ less between user types and consumption levels than for less economically developed countries (LEDC). Many of the MEDC use market-based instruments for water regulation especially the conventional cost-benefit analysis. In Europe full-cost recovery pricing of water is used. This means that the price payed for water by the users (industrial, agricultural or residential) should reflect some of the environmental costs of water production. However, the price of water rarely reflects the true value of water. In LEDC, prices are higher for industrial and commercial users than for public and residential users, enabling low-volume residential users to have access to cheaper water (Boland and Whittington, 2000). This price policy called 'Increasing block tariffs' has not always - depending on the cases - the most efficient results (Boland and Whittington, 2000). The price, in these cases, is related to water use more than water costs. It is generally recognised that for every price there is a quantity supplied and a quantity demanded for each use (Stewart and Howell, 2003). Over the past ten years, world water prices grew by around 6% per year on average (Barker, 1998). Water Conservation (2008) recently

[24]http://www.ucowr.siu.edu/updates/pdf/V118_A8.pdf
[25]http://www.people.hofstra.edu/geotrans/eng/ch9en/conc9en/ch9c1en.html, http://www.nhbs.com/transport_systems_policy_and_planning_tefno_64567.html
[26]http://paginaspersonales.deusto.es/aminondo/Materiales_web/Hummelshaveinternationaltransportcostsdeclined2007.pdf

produced data revealing developments in the world's water industry in 14 Western countries since 2001 (Figure 10.5).

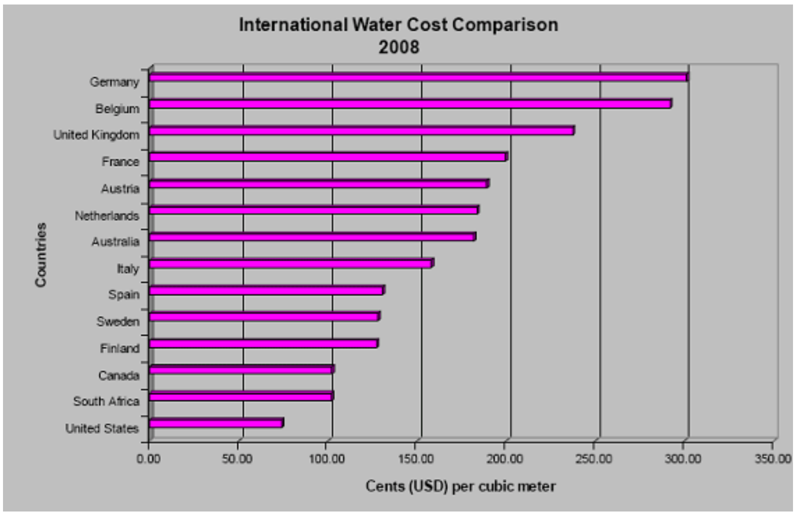

Figure 10.5 Comparison of Water Costs between Countries (credit Water Conservation[27] n.d. n.p.)

The average water and sewerage tariffs varied between a high of 224.6 US cents/m^3 in Denmark, to a low of 65.8 US cents/m^3 in the USA. In Australia the average water tariffs are around 100 US cents/m^3 (AUD1.50 at the time for individuals which have increased by 10% since). Increasing prices were noted in Canada (58% increase) and in Australia (45.4% increase).The OECD (2001) studied water prices for the countries listed in Figure 10.6.

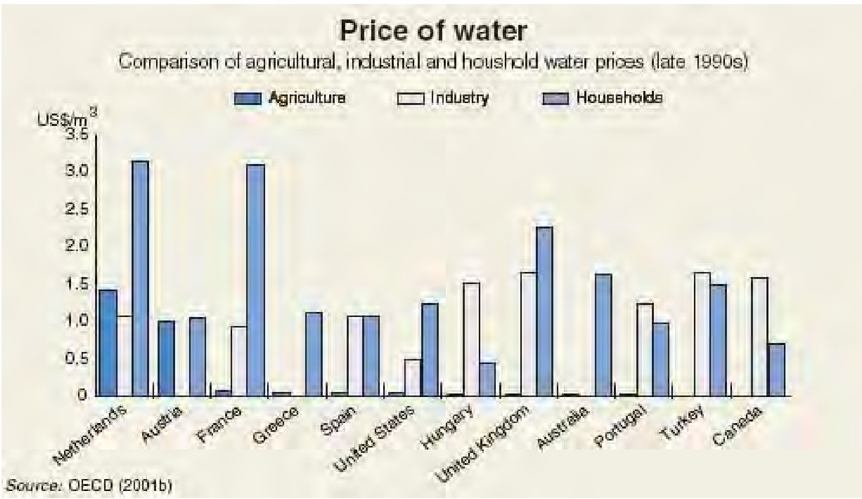

Figure 10.6 Price of Water for Agriculture, Industry and Households (credit OECD, 2001 n.p.)

[27] http://www.waterrhapsody.co.za/tag/environment/

Household, industrial and agricultural prices for water have all increased in Australia since the OECD conducted the research reflected in the figure above (WSAA[28], 2010). The price paid for water by businesses undertaking industrial activities are remarkably low in Australia in comparison to other countries, while households in Australia pay amongst the highest prices in the world. This difference between residential and industrial water prices shows the value of high quality freshwater resources in Australia. The population numbers of Australian cities will increase over the next 20 years, which will in turn increase the demand for water (Table 10.6).

Table 10.6 Illustrative Population Projections for Australian Cities (adapted from CSIRO, 2006[29] Young *et al.*, 2006 p. 25 see also Table 10)

	Population 2001	**Population projection for 2032, Upper limit**
Sydney	4.15 million	4.97 million
Melbourne	3.49 million	4.30 million
Brisbane-Moreton	2.38 million	3.61 million
Adelaide	1.11 million	1.20 million
Perth	1.40 million	1.93 million
ACT (Canberra)	0.32 million	0.35 million

As a nation, Australia's population is expected to grow from 22 million to 35 million by 2049 (Australian Treasury, 2010[30]) placing pressure on capital cities, where the vast majority of the nation's population live, to develop sustainable water resources. In Western Australia - like the rest of the country - the demand for water is mainly composed of agricultural and industrial uses (Figure 10.7).

[28] Water Services Association of Australia, WSAA http://www.wsaa.asn.au/
[29] http://www.myoung.net.au/water/publications/WithoutWater.pdf
[30] http://www.treasury.gov.au/igr/igr2010/, see also http://www.treasury.gov.au/igr/igr2010/report/pdf/IGR_2010.pdf

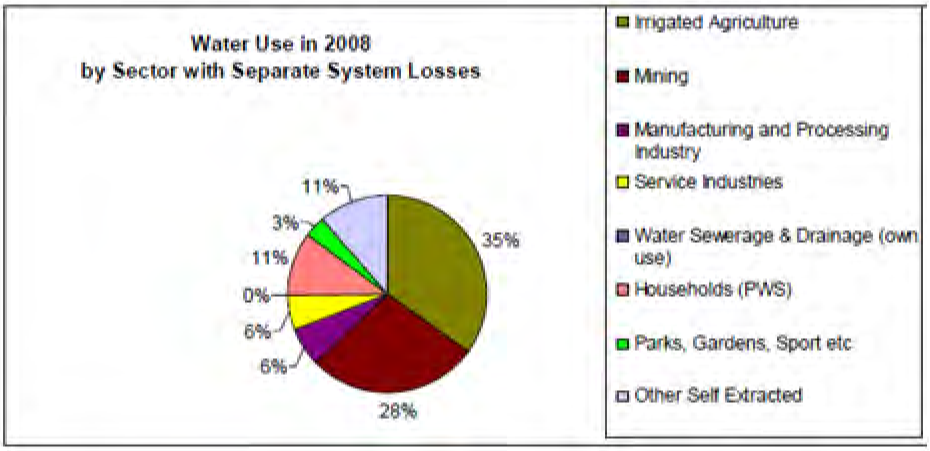

Figure 10.7 Western Australian Water Use by Sector (credit WA Department of Water Thomas, 2008[31] p. 33)

The consumption of water per inhabitant is decreasing as suggest in Table 10.7 which summarises water usage in Australian cities (Marsden and Pickering, 2006).

Table 10.7 Water Consumption in Australian Cities since 1983 (credit NLWR AWR, WSAA[32], 2008, n.p.)

Cities	**Consumption 1983 – 1997 in Gl**		**Consumption 2000 - 2005 in Gl**	
	1983/1984	1996/1997	2000/2001	2005/2006
Adelaide	182.8	214.65	175	167
Brisbane	144.9	184.29	210	250
Canberra	67.5	50.7	58	50
Hobart	19.9	36.6	39	41
Melbourne	406.6	500,0	500	430
Perth	322.0	314.6	320	290
Sydney	473.0	480.9	490	600

However the demand for water and the consumption of water in WA is increasing across all user sectors, including households, industry and agriculture because of population growth, increased urbanisation and greater levels of economic development (Thomas, 2008). Water

[31] http://www.water.wa.gov.au/PublicationStore/first/90954.pdf
[32] National Land and Water Resources
Water Services Association of Australia WSAA https://www.wsaa.asn.au
AWR Australian Water Resource

pricing policies could be used to decrease per capita water consumption levels. Water can be priced directly or indirectly (ARMCANZ [33], SCARM [34] 1996). According to Hatton McDonald (2004 p. 2): “[D]irect pricing involves the setting of prices and charges payable by those who use, reuse and dispose of water. Indirect pricing relies on a variety of mechanisms that reveal the cost of using water and associated resources” which Gardner and Chung (2005[35]p. 3) explain by: “setting extraction limits in water management plans”.

Environmental externalities could thus be reflected in the water price (Hatton MacDonald and Lamontagne, 2005). According to Gardner and Chung (2005 p. 6) “[i]n Western Australia, presently, there is not a well established market in water with clearly defined and enforced water scarcity so direct pricing would be appropriate”.

Water prices could increase significantly in the near future. The water price is expected to grow in the main Australian cities (Young *et al.*, 2006). In Perth the price of water currently varies between AUD0.97/m^3 to 1.98/m^3 according to the volumes of water used in 2010 (WSAA, 2010 p.31[36], WA Water Agency, 2010 n.p.[37]). Table 10.8 shows predictions of water price increases up to 2032.

Table 10.8 Estimated Urban Price of Water in 2032 Under Different Scenarios (AUD/m^3) (adapted from Young *et al.*, 2006[38] p. 31)

Australian Cities	2001 water price	Increase water use	Trade and new resources best scenario
Sydney	1.36	8.09	2.60
Melbourne	1.17	5.96	1.51
Brisbane-Moreton	1.27	10.51	2.17
Adelaide	1.30	1.42	1.61
Perth	1.12	11.40	3.84
ACT	1.11	3.23	1.45

[33] Agriculture and Resource Management Council of Australia and New Zealand
[34] Standing Committee on Agriculture and Resource Management
[35]http://www.edowa.org.au/presentations/Pricing_Water_for_EnvExs-Final_101105.pdf
[36] WSAA Water Services Association of Australia https://www.wsaa.asn.au/Publications/Documents/WSAA%20Report%20Card%202008-09.pdf
[37]http://www.water.wa.gov.au
[38]http://www.myoung.net.au/water/publications/WithoutWater.pdf

Given the trends identified in the table above, infrastructure availability and rates of population growth evident today, Perth's water prices could increase from AUD1.12/m^3 to AUD11.40/m^3 by 2032, an inflation rate of 14%/year (Kaspura, 2006, Young *et al.*, 2006). Sydney's prices could jump from AUD1.36/m^3 to AUD8.09/m^3, while Melbourne's could increase from AUD1.27/m^3 to AUD5.96/m^3. However these estimates correspond to the worst predictions of consumption increase. With an efficient water trading system and the development of new resources, water could be produced and consumed more responsibly and effectively. Moreover, the effects of water trading and land water transportation may mean that price increases could be more moderate. By 2032, prices could be AUD6.33/m^3 in Perth, AUD2.61/m^3 in Brisbane, AUD1.57/m^3 in Melbourne and AUD2.97/m^3 in Sydney. With appropriate management and the development of new water resources the price of water could increase to AUD4.00/m^3 by 2032 in Perth in the best case scenario (Young *et al.*, 2006). This is an inflation rate of 400% over 20 years, or 7.25%/year. An estimation of the benefits of iceberg-derived freshwater resources will be based on a price for water of AUD2/m^3. The Council of Australian Governments and NWI initiated water management reforms. Desalinisation plants are being built (Wonthaggi in Victoria and Kwinana in WA) by specialised companies (Citor, Novatron and Avivapure). Desalination plants raise concerns about capital and running costs as well as about associated environmental costs.

10.7 Iceberg Transportation Costs Benefits Discussion

During the experimental stages of the iceberg transportation proposal outlined above, infrastructural and operational costs are high and incompressible, while energy, maintenance, trade, legal, insurance and environmental costs are minimal and less important. In the technology development phase, the experiments are not expected to be profitable in a short term. The costs of the tests to be conducted have often been estimated to be at least around AUD1 million, and up to AUD50 million (Weeks and Campbell, 1973; Hult and Ostrander, 1978; DeMarle, 1979; Sobinger, 1985): the scientists concerned with this research are often discouraged by these costs and the size of the resource which require large investments.

Based on the calculations performed above, the operational stages of the system proposed in this thesis would all be profitable. For the operational phases at larger scales, energy, maintenance, trade, insurance, legal and environmental costs are all non-linear and actually decrease with the phases of development. The risks associated with the venture are included in the legal, insurance and trade costs. The risks depend of the nature of operations and developments in the technology.

The transportation of icebergs with non-fossil fuels from Antarctica to WA will be compared with the costs for equivalent amounts of water from other sources of supply. Harvesting a 0.1 km^3 iceberg (3 km long, 300 m wide and 100 m high) every year would represent 25% of Perth water resources (3 km^3 for 30 years) and cost about AUD300 million/year. Moreover, iceberg transportation with non-fossil fuels would use less fossil energy, causing less damage to the environment. At the maximal stage (200 million t/year of iceberg freshwater), the annual running cost of the proposal would be low compared to desalination plants, even taking into account uncertainties in transportation technology. For traditional systems of iceberg transportation the operational costs and investments costs depend on the duration of the transportation as explained by Hult and Ostrander (1973[39], p. 37):

> The cost of moving iceberg will depend on the speed. There are two costs factors that are normally influenced by speed in opposite ways, the fuel costs will usually increase with speed, while capital and many operational costs are usually time charges that tend to decrease with increasing speed or less transit time.

The optimal speed is therefore dependent on the fossil fuel consumption and its ratio towards the investments amortisations. To recover the costs the annual costs estimate by Hult and Ostrander are presented in Figure 10.8.

The annual revenue requirements to recover all costs are then estimated as follows:

Amortization of capital investment at a 30-year annual rate of 1/12 of initial investment	$\$37 \times 10^6$
Insurance at 1.5 percent of investment	7×10^6
Power plant fuel	12×10^6
Operation and maintenance of power plant, including nuclear liability insurance	4×10^6
100-man crew other than for power plant	4×10^6
Insulation (∿5000 tons)	15×10^6
Wire rope harness (∿6000 tons)	5×10^6
Special iceberg preparation equipment	1×10^6
Annual cost for acquiring 1.22×10^{13} kg (10^7 acre-ft)	$\$85 \times 10^6$
Cost for 90 percent delivery factor	∿\$7.7/k·m^3 (∿\$9.5/acre-ft)

Figure 10.8 Annual Costs of Iceberg Transportation System (credit Hult and Ostrander 1978 p. 38)

[39] http://www.rand.org/pubs/reports/2008/R1255.pdf

Hult and Ostrander budgeted US$85 million/year for their iceberg transportation project from the Antarctic to California, which would correspond to around AUD600 million/year in 2010 Australian dollars currency. The costs formula of is shown in Figure 10.9.

An approximate analytical representation of the total costs, C_T, is the following:

$$C_T = \frac{C_1}{V} + C_2 V^{\beta\eta - 1} + C_3 V^{\eta} + C_4 , \qquad \text{(C-1)}$$

where $\frac{C_1}{V}$ = costs proportional to time and independent of power, and therefore approximately proportional to 1/V where V is the towing velocity,
$\simeq \$13 \times 10^6$ in the above 1-year cycle illustration,

$C_2 V^{\beta\eta-1}$ = capital costs proportional to time and also dependent on power, i.e., cost $\propto P^{\beta}$ and power, $P \propto V^{\eta}$, and the time dependence represented by 1/V,
$\simeq \$39 \times 10^6$ in the above 1-year cycle illustration,

$C_3 V^{\eta}$ = fuel costs = $\$12 \times 10^6$ in the illustration,

C_4 = costs independent of time, power, or V,
= $\$21 \times 10^6$ in the illustration,

$\beta \simeq 0.7$ for the above power plant and equipment,

η = between 1 and 2 for iceberg trains.

For conventional shipping $\eta \rightarrow 2.0$, but for asymptotic iceberg trains at very slow speeds, Coriolis resistances will dominate at high latitudes and $\eta \rightarrow 1.0$.

The minimum value of C_T with respect to V is obtained for

$$C_3 V^{\eta} = \frac{1}{\eta}\frac{C_1}{V} + \left(\frac{1 - 0.7\eta}{\eta}\right) C_2 V^{0.7\eta - 1} . \qquad \text{(C-2)}$$

For $\eta \rightarrow 1.0$

$$C_3 V \simeq \frac{C_1}{V} + 0.3 C_2 V^{-0.3} ,$$

or the fuel costs are greater than the C_1/V costs.

Figure 10.9 Annual Costs of Iceberg Transportation System of Hult and Ostrander (credit Hult and Ostrander 1973[40] p. 39)

The operational costs of iceberg transportation based on non-fossil fuel consumption do not rely on speed. However, the investment amortisation costs are highly time dependent. There would be a constraint on scheduling. The savings in fossil fuel costs would largely offset the investment amortisation costs (evaluated at less than 10% per year). Amortisation costs and capital recovery would depend on the duration and scale of iceberg transportation projects. At this stage, the evaluations are crude approximations. To achieve more precise estimates, the transportation operation should be modelled in detail. Assuming that the iceberg transportation system identified in this thesis would be technically feasible, it is possible to undertake a Cost-Benefit Analysis (CBA) to evaluate its economic feasibility. The analysis

[40] http://www.rand.org/pubs/reports/2008/R1255.pdf

would include amortisation of capital expenditure and assessment of the break-even time for the investment.

10.8 Cost-Benefit Analysis

A CBA evaluates the economic feasibility of a project (Slack[41], 2010). Specific and pre-determined parameters and sensitivity analysis involve the introduction of uncertainty variables in the calculation such as inflation rates or energy charges (Breierova and Choudhari, 2001[42]). CBA are based on assumptions on spatial, temporal and technical elements (OECD,2003; UN, 2003). It is possible to design various scenarios. According to Rodrigue (2009[43] see also Table 10.9):

> Modal variations in efficiency will depend heavily on what is to be carried, the distance travelled, the degree and complexity of logistics required as well as economies of scale ... upon the complementarities of cost-efficient and time-efficient modes, seeking a balanced compromise rather than an ideal or perfect equilibrium.

Table 1098 Iceberg Water Transportation CBA Parameters for a Large scale Project

Parameters		**Iceberg Transportation Project**
Pre-determined parameters	Spatial	From Antarctica to Australia
	Time	Over 10 years
	Social	Drinking water uses
	Technical	Capital and Operating Costs known
Sensitivity analysis	Inflation	Variable
	Water costs	Variable
	Fuel costs	Minimised
	Uncertainty aspects	Technological issues, scales coefficient
Economic feasibility	Robustness of the predictions	Through the coefficient
	Various scenarios	Technological issues

[41] http://people.hofstra.edu/geotrans/eng/ch9en/meth9en/ch9m1en.html
[42] http://sysdyn.clexchange.org/sdep/Roadmaps/RM8/D-4526-2.pdf
[43] http://people.hofstra.edu/geotrans/eng/ch3en/meth3en/ch3m2en.html

There are several measures obtained from CBA techniques to aid decision making:

- the Net Present Value (NPV);
- the Internal rate of return (IRR). It is the average rate of return on investment costs over the life of the project. The opportunity cost capital corresponds to the required rate of return for a nil NPV. Risk probability has to be discounted. Higher risks require higher rates of returns. Investments with rates of return higher than opportunity cost of capital are accepted;
- the Cost-Benefit Ratio shows "how much profit will result from an investment. It is calculated by taking the [NPV] of expected future cash flows from the investment and dividing by the investment's original cost" Farlex Financial Dictionary (2009[44] n.p.). According to Farlex Financial Dictionary (2009[45] n.p.): "[A] ratio above one indicates that the investment will be profitable while a ratio below one means that it will not. A cost-benefit ratio is also called a profitability index";
- the Total Factor Productivity is a measure of the productivity of an investment;
- the Factor substitution shows which type of factor is more important between capital and labour.

With these CBA indicators it is possible to undertake a sensitivity analysis to study how the variation (uncertainty) in the output can be according to Saltelli *et al.* (2008[46] n.p.): "distributed, qualitatively or quantitatively, to different sources of variation".

CBA are used to evaluate under specific assumptions, the effects of dependent variables on several values of an independent variable. Sensitivity analysis establishes the range of value of a specific variable in function of its actual outcome (Breierova and Choudhari, 2001[47]). CBA generates several scenarios. It involves changing various input values to see the effect on the output value.

Table 10.10 shows CBA measurements for a large iceberg transportation project. In this sensitivity analysis the main uncertainty parameters are economic and technological. The technological analyses were based on the worst scenario at different scales (28% of increase of the costs). A specific technological reliability coefficient was introduced to assess the validity of the technological assumptions of iceberg water transportation and the cost of

[44] http://financial-dictionary.thefreedictionary.com/Profitability+Index
[45] http://financial-dictionary.thefreedictionary.com/Profitability+Index
[46] http://onlinelibrary.wiley.com/doi/10.1002/9780470725184.ch1/summary
[47] http://sysdyn.clexchange.org/sdep/Roadmaps/RM8/D-4526-2.pdf

the developments of the waterbag and the kite technologies. The fact that technological elements are predominant in the capital division of the factor of substitution is characteristic of high technological projects and demonstrates that technological factors are not reliable. Therefore, the choice of the worst case scenario is justified. The unreliability of renewable energy technologies can trigger the rate of productivity of transportation projects (Nordhaus, 1979). In normal and best case scenarios all the CBA are positive. This means that assuming the technical feasibility of the iceberg transportation system using non-fossil fuels it would be economically feasible at a large scale. The scales and prices are therefore the main variable parameters.

Table 10.10 CBA Measurements for a Large Iceberg Transportation Project

Stages	**Stage 3: 3.5 million m^3**	**Stage 4: 25 million m^3**	**Stage 5: 200 million m^3**	**Stage 6: 2 billion m^3**
Uncertainty coefficient	1.28	1.28	1.28	1.28
Inflation lower limit	2%	2%	2%	2%
Inflation upper limit	7%	7%	7%	7%
Total value (currently) in AUD 1	7 million	50 million	400 million	4,000 million
Capital costs in AUD	8.2 million	40 million	180 million	1,035 million
Operating costs in AUD	4.8 million	30 million	170 million	1,100 million
Total costs	13 million	70 million	350 million	2,135 million
Rate of return 1	0.015	0.016	0.017	0.02
NPV 1	-2,346,000 (-18%)	-6 million (-12%)	45 million (+14%)	160 million (+15%)
Benefit-cost ratio 1	0.53	0.7	1.14	1.41
Total value (of 2020) in AUD 2	10.5 million	80 million	600 million	6,000 million
Rate of return 2	0.0065	0.016	0.019	0.022
NPV 2	-320,000 (-2%)	+11.5 million (+25%)	+150.6 million (+83%)	+2,200 million (+215%)
Benefit-cost ratio 2	1.015	1.14	1.71	2.12
Input	10.5 million	80 million	600 million	6,000 million
Output	13 million	70 million	350 million	2,535 million
Total Factor Productivity	0.8	1.15	1.70	2.35
Labour	4.8 million	31 million	300 million	1,800 million
Capital	8.2 million	40 million	280 million	1,035 million
Factor of substitution	0.58	0.775	1.07	1.7

These calculations are based on scales and price variations of water. For a water price of AUD2/m^3 (net price, including taxes) the cost benefit ratio is over 1 for large scale projects only. Similarly, NPV is positive only for large projects over 200 million t. Since environmental benefits are not included in the analysis, the low levels of greenhouse gas emissions associated with the proposed technology would mean actual NPVs would be higher than indicated and projects on an average scale are more likely to have a cost-benefit greater than 1.

For a water price of AUD3/m^3 the CBA ratio predicts for all the scales a strong benefit which is larger than any other type of water transportation system for the same volume. The NPV are positive. Further inflation of water prices in Australia could be estimated. An uncertainty coefficient of funding could also be set, corresponding to the uncertainty of finance of the project. Given the prices of water in Australia, cities like Perth could therefore strongly benefit from an iceberg transportation project.

10.9 Sustainable Technologies

The sustainability standards for large water project operations are changing (for example in new regulations of maritime transportation with fuel emissions taxes), which will affect relations between costs and benefits, access and uses, values and demand. However, sustainable energies tend to have high development costs and low short term returns. Clean and sustainable transportation or alternative clean water operating systems have high equipment costs and low rates of amortisation, efficiencies, flexibility and predictability (Rosen, 2009). Existing technologies and means of transportation based on fossil energy continue to be competitive. The continuing supremacy of petroleum fuels can be explained by their efficiency in terms of combustion and design. World fossil fuel energy consumption increased by 40% between 1980 and 2000 (Rodrigue, 2009). Transportation activities rely mainly on fossil fuels because of the amount of investments in developing technologies relying on petroleum.

Nevertheless, renewable energy is becoming more competitive as the cost of fuel increases: in 2008 oil topped US $150 a barrel. Global reserves of oil represent about a trillion barrels, which corresponds to 30 years of reserves at present rates of consumption. The demand for oil is growing. Major oil producers will not meet increasing world demands (Mass, 2005). Fuel prices will rise. According to Rodrigue (2009 n.p.[48]): "economists have demonstrated that automotive fuel oil is price inelastic. Higher prices result in very marginal changes in demand for fuel". Fuel prices increases can stimulate the development of alternatives energy

[48]http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/ch8c2en.html

sources as energy consumption is very cost sensitive. Renewable fuels energy sources will be more competitive with future price increase of petroleum fuel (Nel and Cooper, 2008). According to Rodrigue (2009[49] n.p.):

> The analysis of the evolution of the use of fossil fuels suggests that in a free market economy the introduction of alternative fuels is leading to an increase in the global consumption of both fossil and alternative fuels and not to the substitution of crude oil by bio-based alternative fuels. In the initial phase of an energy transition cycle, the introduction of a new source of energy complements existing supply until the new source of energy becomes price competitive to be an alternative.

Fossil fuels consumption is not substitutable by non-fossil fuels which are used in parallel. Alternative fuels could become the major source of energy only with the development of devoted technologies based on their specific uses coupled with strong regulatory interventions to encourage their use especially in the case of transportation (Pascala and Socolow, 2007). Other activities, including those in industrial, commercial and household sectors, tend to have greater price elasticity and are more likely to transfer from fossil fuels to alternative energies as the price of oil increases. The costs of non-fossil energy are generally high for transportation activities than: as the consumption of fossil fuels is higher, the price for these fuels is more negotiated and therefore lower and more competitive. In this view, shipping is likely to be relatively unaffected by higher oil prices to start with, but energy costs represent an important contribution to shipping costs (Notteboom and Rodrigue, 2005). The shipping industry adapts to higher energy prices by decreasing speed (Hummels, 2007[50]). According to Rodrigue (2009 n.p.[51]): “On the long run, higher energy prices may however indirectly impact maritime transportation by lowering demand for long distance cargo movements”.

Activities will select sites of manufacturing facilities closer to markets, and eventually restructure the links between production and distribution. These two trends are fundamental: in order to switch to renewable energies, maritime transportation systems have to be competitive at lower speeds and shorter distances. Price increases have significant impacts on consumption, means of transportation, transportation structures and management. At the same time, alternative, renewable energy-based transport systems will develop in niche

[49] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/ch8c2en.html
[50] http://paginaspersonales.deusto.es/aminondo/Materiales_web/Hummelshaveinternationaltransportcostsdeclined2007.pdf
[51] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/ch8c2en.html

markets where they can be competitive over particular distances and speeds. Skysails and Kiteship provided models of kite-assisted sailing technology offering costs savings (Figure 10.10 and Figure 10.11).

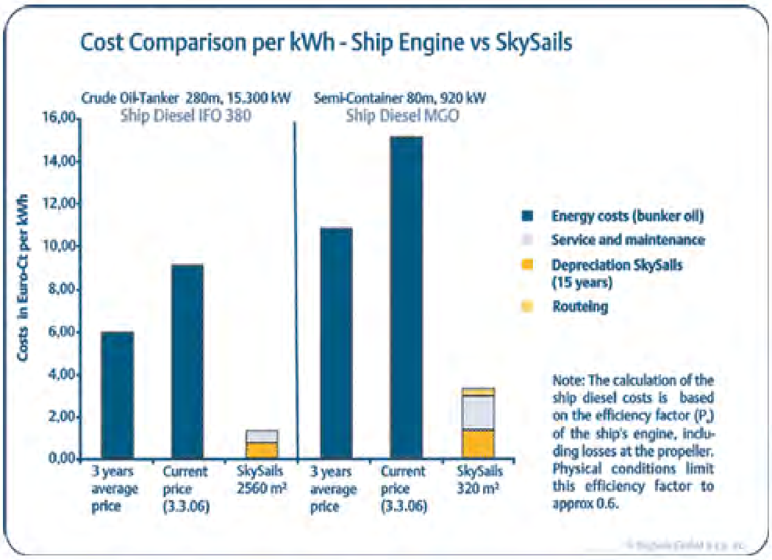

Figure 10.10 Kite Cost Comparison (credit Skysails GmbH&Co.KG, 2007[52] n.p.)

[52]http://gcaptain.com/maritime/blog/ocean-kites-top-10-green-ship-designs?1034

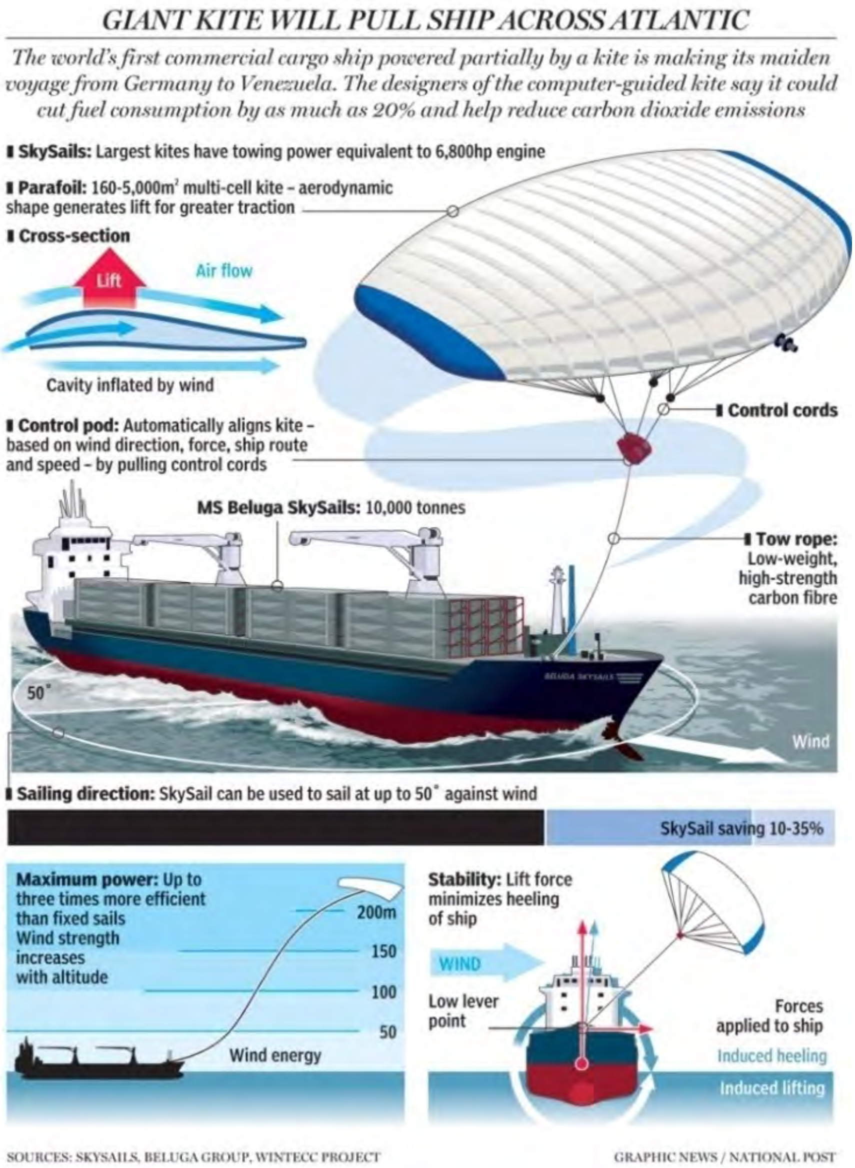

Figure 10.11 Kite Cost Comparison (credit Skysail, Wintecc, 2007[53] n.p.)

In the Skysail model for cargo sailing, a limited part of the sailing could be undertaken by the kite system depending on time requirements and climatic conditions (Figure 10.12).

[53]http://gcaptain.com/maritime/blog/ocean-kites-top-10-green-ship-designs?1034

Figure 10.12 Skysail (credit Skysails GmbH&Co.KG, 2007[54] n.p.)

With these limitations Skysail estimate savings of 20% on the cost of the fuel consumption of a cargo sailing powered by both a fuel propulsion system and a kite system compared to a cargo sailing only powered by a fuel propulsion system. However in the case of iceberg transportation, time requirements would not be as precise as for cargo sailing and climatic conditions would be more appropriate regarding the strength and periodicity of winds. These economic impacts would need further investigation.

For the sustainable iceberg transportation systems identified in this thesis, smaller distance, lower speed, and less service are therefore significant economic factors. It is because its technological structure is based on these principles that the transportation system identified in this thesis can be economically viable. In particular, the proposed operating system is sustainable because the iceberg resource is renewable. The concept of renewability revolves around the resource being capable of replenishment over a period (Rodrigue, 2009). Ground resources and land ecosystems are over stressed by water supply operations and have a more crucial need for the freshwater in quantities and in qualities than marine ecosystems (Thomas, 2008). Roberts *et al.* (2005) discussed the water supply market in Australia and its negative externalities such as significant environmental impacts or economic decline[55]:

[54] http://gcaptain.com/maritime/blog/ocean-kites-top-10-green-ship-designs?1034
[55] http://www.treasury.gov.au/documents/1087/html/docshell.asp?URL=05_Water.asp

> The environmental damage caused by the current allocation of water threatens not only habitat and biodiversity but also rural output through degraded land and water quality. This results in excessive water wastage and disincentives to invest in water saving infrastructure and limits potentially economically beneficial changes to industry composition.

Western Australian environments could benefit from iceberg transportation such as waterways, wetlands, cave systems, estuaries and inlets, and forests/vegetation (Beckwith, 2009). Associated social benefits could be the increase of heritage, education, aesthetic, or recreation values of these environments. Activities such as walking, birding, picnicking, and fishing could benefit indirectly from an iceberg transportation system. In Western Australia, the price of water could recover the costs of environmental externalities management, water resource management, through several legal measures, by reflecting the different types of water usages (Hatton MacDonald and Lamontagne, 2005; Gardner and Chung, 2005; WA Department of Environment, 2005). Hatton MacDonald cited by Gardner and Chung[56] (2005 p. 6) suggested that: "the costs of research and monitoring environmental impacts do not vary in the short term and should be incorporated in the fixed charge".

In conclusion, the economic characteristics of iceberg water transportation systems identified in this thesis are that they are sustainable and that they could have low running costs. However, these transportation systems have to overcome issues of lower efficiencies of alternative fuels, and large capital investments. These characteristics can be used to compare iceberg transportation with other water supply technologies.

10.10 Comparison with Other Water Supplies

The preliminary calculations made by IWHG suggest that US$500 million (AUD620 million) would have to be spent for five years to develop an advanced iceberg harvesting technology and that an annual supply of approximately 2 km^3 for US$1 billion. Water could be sold at a price of US$0.50/$m^3$. The transportation calculations are based on a 10 million m^3 iceberg and the costs of a fossil fuel towing system are not accurately evaluated. The costs of such a transportation system could overtake its benefits (more than AUD5/l) (Smakhtin *et al.*, 2001, Table 10.11).

[56] http://www.edowa.org.au/presentations/Pricing_Water_for_EnvExs-Final_101105.pdf

Table 1. A Summary of Unconventional Sources and Options for Water Supply in South Africa

Source/Option	*Potential for Supply or Envisaged Effect*	*Level of Technological Development*	*Level of Current Implementation or Use*	*Costs*	*Comments*
Surface Water resources within South Africa	Additional 14,000 Mm^3/a	Engineering structural solutions: well developed	Approximately 19,000 Mm^3 are currently allocated	US\$0.04–0.15/m^3	Costs for existing water supply systems: converted to US\$ using "DWAF (2000): Charges"
Deep Storage	Possible increase in a reservoir yield up to 90% of the MAR	Similar to structural solutions above	Not implemented	Capital investments increasing linearly with the storage	
Congo Water	10% of the Congo River MAR exceed all surface water resources of South Africa	Existing engineering practices could be used for some transfer options	Not implemented	Tankers: US\$2.45/m^3 Bags: US\$2.7/m^3 Pipeline: US\$5.3/m^3	
Virtual Water	Indirectly involves the water resources of all SADC countries	The concept is not developed	Not implemented	No direct estimates are possible	
Deep Groundwater	A maximum of 1,000–1,300 Mm^3/a in Western Province only	Deep drilling technology is in place	Not implemented	Not available	Potential for supply is approximated at 50% of the reported recharge figures
Artifical Recharge	Storage of surplus water and the increased efficiency of use	Developed to the level of practical implementation	Pilot experiments	Not available	
Iceberg Water	Unlimited	Requires intensive research and international cooperation	Not implemented	US\$500M over 5 years to develop the technology	Very preliminary cost estimates for technology development
Seawater: Desalination	Unlimited	Developed to the level of practical implementation	Limited use (<0.2 Mm^3/a)	US\$0.5–7/m^3	
Seawater: Direct Use	Unlimited	Not developed	Not implemented	Not available	
Rainfall Enhancement	Local increase in rainfall amounts	Developed to the level of practical implementation	Pilot experiments	0.01–0.02 US\$/m^3 of enhanced rainfall	
Fog Collection	On average 180–230 l/day in foggy days	Developed to the level of practical implementation	Pilot experiments	US\$0.37/m^3–0.43/m^3	Localized water supply only
Effluent Reuse	990 Mm^3/a	Developed to the level of practical implementation	30 Mm^3/a	Not available	The potential is limited by the total volume of effluents to be treated
WDM	Potential reduction of system water losses up to 30–40%	Multiple measures with varying degree of development	Implemented by several municipalities	Not available	

Table 10.11 Water Options for South Africa (credit Smakhtin *et al.*,[57] 2001 p. 31)

[57] IWRA, Water International, Volume 26, Number 3, http://www.waternet.co.za/we/docs/pete_unconventional_sources.pdf

According to Hult and Ostrander (1973[58] p. 9):

> If the potential iceberg resources were exploited (1,200 km^3 per year) the transporting of the icebergs would ultimately involve an annual business of about US$10 billion per year. The total cost of the delivery for wholesale distribution of high quality fresh water would be about US$30 billion to US$50 billion per year. The savings over desalting or long distance interbasin transfer could ultimately amount to US$50billion to US$70 billion per year … An amount of less than 10 percent of the potential harvest ... would have a direct economic impact of US$2 billion to US$5 billion per year".

More recently a Canadian study undertaken by (Lefrançois *et al*., 2008[59]) reported results of US$200 million (AUD270 million) for towing of a 500 million m^3 tabular iceberg in ideal conditions. These reports considered the price of fuel emissions and ice melting, but did not include operational management costs, environmental costs, and the costs of developing the technology. A full cost analysis would not show profits. Estimates of Rowden-Rich (1986, 1987) are presented in Appendix 5. The cost of 3DS / Mougin project is evaluated to be around 10 million dollars which would comprise the skirt, five months of diesel fuel for the tugboat, and the crew work and the distribution of the fresh water at the destination. However only 5 million t of water would be obtained which correlates with our results and estimates. Moreover these costs do not include the melting process costs of the iceberg, These estimates are all related to transportation systems based on fossil fuel consumption. With a comparable overall costs analysis they would be at least one degree of magnitude higher than the estimates of an iceberg transportation system based on currents and kite transportation. Costs associated with a project to transport iceberg freshwater from Antarctica to WA can be compared with costs for desalination, shipping and pipeline supply of the same amounts of water (Chrisholm *et al.*, 1993; AFT, 2009[60]). For a towing tug shipping 2 billion m^3 over 10 years over 2,800 km, the towing cost depends strongly on energy costs.

The energy for one delivery in 3 months, E, at 5% efficiency to transport the iceberg train is around: E = 100,000 x 2,200,000 + 2,000,000,000 x 2,200,000 x 20 = 8 million GJ. This energy corresponds to the consumption of diesel fuel for 3 months of 2 million t. The cost for diesel fuel is AUD2 billion per delivery. The fuel emissions to produce them could be around

[58] http://www.rand.org/pubs/reports/2008/R1255.pdf
[59] http://ltte.gmc.ulaval.ca/Publications%20(va)%20-%20LTTE.html
[60] http://www.farmhand.org.au/downloads/82-93_Producing_more_%20water_Part_8.pdf American Farmland Trust

10 million t of CO_2. Which means for AUD32/t of CO_2 an additional environmental cost of AUD320 million. For the materials fuel emissions would produce 5 million more tonnes of CO_2. For comparison we saw that iceberg transportation based on non-fossil fuel energies would cost about AUD5 million in fuel at the same scale and would produce 20,000 t of CO_2. Differences of iceberg water displacement benefits between iceberg towing projects based on fossil fuels and iceberg water towing projects using renewable energies are significant.

Costs for dam and pipeline supplies, as well as recycling and desalination, are available from the latest projects or proposed projects in Australia (Table 10.12).

Table 10.12 Comparisons of Water Projects Costs and Capacities and Gas Emissions in Australia

Water Systems	**Capacity (GL over 30 years)**	**Location**	**Cost AUD billion**	**Cost AUD per t**	**Greenhouse gas emissions in millions of t**	**Cost AUD per t adjusted with emissions costs**
Wonthaggi desalination plant	4,489.50	Victoria	6[61]	1.3	40	1.8
Port Stanvac desalination plant	2,956.50	South Australia	5[62]	1.7	15	1.9
Kurnell desalination plant	2,737.50	NSW	5[63]	1.83	15	2
Kwinana desalination plant	1,576.80	WA	1.2[64]	0.76	15	1.6
Tugun desalination plant	1,368.75	Queensland	1.7[65]	1.24	6	1.8
Dam and pipelines	5,000	Several	10	2	5	2.5
Recycling	5,000	Several	10	2	0.5	2
Shipping	6,000	WA	70	11.6	70	13
Iceberg	6,000	WA	7+4*	1.9	1.2	1.9

*finance and institutional costs

[61] http://www.vicwater.org.au/index.php?sectionid=969 see also http://en.wikipedia.org/wiki/Wonthaggi_desalination_plant
[62] http://www.abc.net.au/news/stories/2009/09/08/2680138.htm, http://en.wikipedia.org/wiki/Port_Stanvac_Desalination_Plant
[63] http://en.wikipedia.org/wiki/Kurnell_Desalination_Plant
[64] http://www.watercorporation.com.au/D/desalination.cfm see also http://en.wikipedia.org/wiki/Perth_Seawater_Desalination_Plant, http://www.energyrecovery.com/index.cfm/0/0/64-In-the-News.html,
[65] http://www.watersecure.com.au/what-we-do/desalination http://en,wikipedia.org/wiki/Gold_Coast_Desalination_Plant

The table is based on the figures of the water suppliers (the price of water for the desalination plants). Greenhouse gas emissions were based on the figures of water suppliers or estimated, but did not include in the case of desalination the costs of cleaning and recycling chemical wastes. The table shows that iceberg transportation cost per tonne is competitive. Iceberg transportation is a more economical and sustainable transportation system. Large transportation projects costs such as desalination are often underestimated (Flyvbjerg *et al.*, 2002[66]). Desalinated water prices would increase if environmental externalities were taken in account. It becomes the lowest cost when greenhouse gas emissions costs are included. Desalination is a promising type of water supply and will become more competitive with renewable energies uses and efficient recycling technologies of the associated wastes. Recycled water costs are detailed in Table 10.13.

Table 10.13 Recycled Water Costs (credit ATSE[67], 2004 p. 146)

Location	**Use**	**Cost c/t**
Parafield, SA	Wool scouring	30
Springfield	Residential Supply for non-drinking use	145
Newington NSW	Residential Supply for non-drinking use	160
Melbourne, Vic	Integrated design for residential development	250
Melbourne Eastern, Vic	Integrated design for residential development	> 300
Rouse Hill, NSW	Residential Supply for non-drinking use	300-400

Recycled water is a sustainable type of water supply with low associated greenhouse gases emissions (Economic Regulation Authority Western Australia, 2009[68]). A tug project based on nuclear energy could be competitive on the long run if the costs of the wastes and the risks associated can decrease substantially.

Based on these evaluations of costs I can conclude that the process based on transporting icebergs using bags and kites technologies identified and selected for the transportation from Antarctica to Australia is cost effective. Iceberg transportation projects could be profitable. The evaluations should be reviewed from one stage to another, with exhaustive cost studies and updated price ranges.

[66]http://flyvbjerg.plan.aau.dk/JAPAASPUBLISHED.pdf
[67]http://www.environment.gov.au/soe/2006/publications/drs/pubs/571/set/hs44radcliffe-water-recycling-in-australia.pdf
[68]http://www.erawa.com.au/cproot/7359/2/20090306%20Final%20Report%20-%20Inquiry%20into%20Pricing%20of%20Recycled%20Water%20in%20Western%20Australia.PDF

10.12 Conclusion

After assuming the technical feasibility of iceberg transportation systems from the AAT to WA based on non-fossil fuels and liquid freshwater transportation in previous chapters, this chapter investigated their economic feasibility. According to Rodrigue and Comtois (2009[69]):

> Within the transport sector, there are significant differences between speed, energy costs, mode, type of loads [and economies of scale]...Overall, transport operators seek a compromise between speed (returns in overcoming distance) and energy (costs in overcoming distance). The lowest energy consumption levels are associated with bulk freight travelling at slow speed (like oil) while high levels correspond to passengers or merchandises being carried at high velocities.

To be economically feasible, the route should be covered at a minimal cost even if it requires longer durations. Transportation using non-fossil energies is based on the principle of minimising the time requirements of the service to optimise the distance costs (Field, 2001).To assess if iceberg operating is economically viable, the level of reliability and sustainability of wind, currents, and environmental outputs were estimated in economic terms. Even in the worst case scenarios such an iceberg operating project from Antarctica to WA may produce attractive capital return at large scales in comparison with desalination technology (Richardson, 2005). Iceberg transportation using non-fossil energies, could have high environmental and social benefits. Without including them, the minimal cost of 1 l of iceberg water on the base of a large scale transportation system costs is AUD0.002/l or AUD2/t, the same price range as Sobinger and Rowden-Rich in their estimations (Rowden-Rich, 1987; Sobinger, 1986). Note that the prices of Sobinger and Rowden Rich operating systems would be higher today because of inflation over the 30 last years. World average water prices increased during this period and will continue to increase. They could reach 4 AUD/t by 2020 according to low estimates (Moran, 2008[70]). The costs and benefits of the iceberg transportation system were detailed and can be analysed in terms of fixed and variable uncertainties:

- with average uncertainties of returns, an iceberg transportation system should be developed at a larger scale;

[69] http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/energymode.html
[70] http://www.ipa.org.au/library/publication/1222147673_document_moran_watersupply-melbourne.pdf

- with low uncertainties of returns, an iceberg transportation systems could be developed at a small scale.

These iceberg transportation cost calculations can provide information about the costs for investments, operation and the distribution of freshwater. Taking into consideration the environmental and political aspects of the water market, iceberg operating projects would need to be sustainable in terms of ecosystem and environmental considerations to be economically efficient (Tolley and Turton, 1995). Iceberg water operations could have a particular place in this market, depending on their range, and the nature of other water resources in the accessible regions and the nature of their uses.

Chapter 11 Conclusion and Future Perspective

Figure 11.0 Tabular Iceberg (credit Scott Polar Institute Dowdeswell 2008[1])

The poetry of the world calls again and again for
propositions and understandings.
(Translated from Onfray 2006 p.126)

[1] http://www.spri.cam.ac.uk/research/projects/larseniceshelf/photos/AP-tabular-iceberg.jpg

Chapter 11 Conclusion and Future Perspective

Existing traditional water transfer systems are reaching their limits. Mass land freshwater transportation, dams, channels, aqueducts and pipelines have been used extensively. Nowadays available drinking water circulates in a closed system and the volumes supplied cannot be increased inexpensively. They have to be shared out among fast growing populations and needs. Alternative freshwater resources are available such as the desalination of seawater, rainmaking, the artificially produced water and icebergs. The idea of towing icebergs has been under consideration since 1890, but has been repeatedly dismissed because of overwhelming technological and financial difficulties associated with it. In Australia, the lack of freshwater has spurred interest in iceberg transportation. When in the 1980s the AAD noted (Parliament of Australia, 1985 p. 3, Senate p. 710): Antarctic ice "an enormous potential to supply Australia, and even such water poor areas as Northern Africa and the Middle East", economic and ecological sustainability were not commonly accepted priorities (Allan, 1996). This partly explains why iceberg transportation projects failed later. Up to that time, most projects relied on high consumptions of fossil fuel energy, which often is not cost efficient for transportation of bulk materials. The aim of this thesis is to investigate conditions for the sustainable transportation of iceberg freshwater from the AAT to WA. The findings will be first presented. This will help to discuss how the aims and objectives have been addressed, to describe the outcomes of the PhD and to suggest future research.

11.1 Concluding Remarks

Transportation Geography is more than just a simple description of technical performances. Transportation plays a pivotal role in economic development, requiring reflection on inter-relationships between component systems and careful consideration of scale and technology. This is particularly so in the development of new systems such as transportation of iceberg freshwater. The thesis identifies the prerequisites for an efficient system for icebergs freshwater transportation involving new technologies, including the need:

- to rationalise the transportation system in order to make it economically feasible with bags;
- to avoid melting water loss and;

- to use sustainable technologies and environmental friendly materials to transport icebergs using maritime currents and kites.

11.2 Findings

This thesis on iceberg transportation from Antarctica to West Australia presents a thorough synthesis of current knowledge concerning iceberg transportation. Geographic, environmental, economic and legal analyses provide a theoretical basis for recommendations, while technical analyses address practical considerations. The main findings of my research are:

Chapter 1 identifies a freshwater need in WA. WA is ideally located in terms of geographical proximity to Antarctica and maritime currents for icebergs transportation. WA has the infrastructure needed to receive iceberg freshwater.

Chapter 2 and Chapter 3 conclude that tabular icebergs are the most suitable for water transportation projects (Figure 11.1). However, the extreme mass of these icebergs and the climatic conditions specific to the Southern Ocean present huge physical and geographical obstacles.

Figure 11.1 Drifting Plateau Iceberg Piece in Antarctica off the Ross Ice Shelf (credit Alfred Wegener Institute for Polar and Marine Research Polarstern expedition ANTXXIII/8, Weddell Sea, 2007[2] n.p.)

[2]http://www.awi.de/fileadmin/user_upload/News/Selected_Topics/Biodiversity/Life_below_Ice_Shelves/Photos_for_Download/Landscapes/20070114_Iceberg_GChapelle.jpg

Chapter 4 concludes that harvesting icebergs would have minimal impacts on marine and terrestrial ecosystems.

Chapter 5 research related to iceberg transportation from the AAT to WA is not well developed. Previous projects failed because they were not economically feasible: fossil fuel costs were the main problem. Alternative transportation systems therefore should be investigated. Analysis of previous iceberg transportation projects identified a number of innovative operating principles:

- to bag the iceberg in situ;
- to carry the iceberg in a megabag in warmer waters and stabilise it by using a net;
- to melt the iceberg in the megabag and to recover the freshwater in bags;
- to transport the freshwater in a train of bags powered mainly by maritime currents and winds.

Chapter 6 shows that specific iceberg detection and harnessing techniques exist. Technologies using waterbag, wind and maritime currents-based transportation systems are available. These technologies could increase the flexibility and versatility of the elements of a new transporting/operating system proposed in this thesis. Transportation distance and fossil fuel consumption should be minimised to reduce the operating costs of transporting big volume icebergs and melted freshwater.

Chapter 7 describes a new and original model for a more economical and sustainable iceberg transportation system. The model proposes a new technology for wrapping iceberg in a megabag and manipulating the resulting melted freshwater in trains of freshwater bags from melted sites to destination, with natural drifts and wind propulsion with kites. The new logistic aspects for a sustainable iceberg transportation system are:

- iceberg selection (iceberg detection, definition of the zone for harvesting and environment assessment);
- icebergs operation (capture, harnessing and bagging with a covering sheet);
- icebergs wrapping (collar installation for the collection of melted freshwater, wrapping with a megabag, netting and protecting with an optional self sustaining structure);

- freshwater processing (manoeuvring and connecting of the small bags to the collar, water transfer in small bags, composing a train of freshwater bags, launching the freshwater bags into the maritime currents);
- bag transportation train sailing techniques;
- freshwater transportation using currents drift for the pre-selected destination and kites for propulsion with wind.

Further research is needed to test this model in order to assess its technical feasibility in Southern Ocean conditions. Experiments could investigate:

- the melting patterns of icebergs;
- the naval characteristics of the iceberg bags (stability);
- the maritime conditions (currents and winds);
- the naval characteristics of the waterbags operating conditions (the metacentric height Gm, the drag...);
- transportation systems with currents and kites (propulsion, pull, installation, driving abilities of the kites).

Chapter 8 shows that such an iceberg transportation model would have several environmental benefits:

- a limited number of tabular icebergs would be selected for freshwater transportation from Antarctica to WA or other preselected destinations. Icebergs would be mainly operated in the high seas where they have small or negligible impacts on the environments. Physical disturbances of the ecosystems produced by icebergs transportation have less adverse impact on the environment than the construction and operation of dams, water channels and desalination plants. The fact that the iceberg is wrapped in a megabag would limit the thermal/salinity/chemical gradients and any ecological disturbances associated with iceberg transportation;
- the transportation system described would consume less energy than that used for the construction and the maintenance of the infrastructures needed by dams, channels, pipelines and desalination plants, or for water transportation by vessels;
- the manufacturing of the materials for bags and kites and the proposed transportation system would consume less fossil fuel energy than that required for traditional dams,

channels, and desalination plants. CO_2 emissions associated with a current and kite based transporting system would be minor;
- compared with other water supply systems (dams, channels, pipelines, desalination plants) the risks of accidents, pollution, and ecological disturbances are minimised by waterbag transportation using natural energies (maritime currents and winds);
- however, some risks of icebergs transportation exist. They have potential environmental site-related impacts and transit-related impacts on the oceans and at destination, such as the effects induced by the light distribution in sea water, the sheltering, biological impact and the potential instability of megabags during transportation, the harvesting of tabular icebergs with traditional vessels and technologies. These effects would be close to the natural effects of icebergs drifting and it can be conceived that local ecosystems could respond to the thermal/salinity/chemical gradients and ecological disturbances induced by transportation.

Several protection measures could be implemented to limit potential environmental damage:

- potential ecological sensitive modification should be tested first on relatively small size icebergs;
- iceberg harvesting should be limited to specific high sea zones. A zoning system would limit the potential environmental damage induced by icebergs transportation;
- icebergs capture could follow the methodology defined by the International Ice Patrol, minimising the dangers for navigation and operating with minimal ecological disturbance;
- residual mineral elements contained in icebergs associated with plankton blooming could be replaced by a compensation process of the mineral elements filtered and collected at the bottom of the iceberg bag.

The ecological impacts can be reduced to non-significant minor and transitory levels.

Chapter 9 explains that the legal circumstances of iceberg transportation are complex. An iceberg transportation regulation could be regulated by an executive and representative iceberg operating organisation in respect of the regimes of the LOSC and the ATS to ensure maximal environmental protection.

Chapter 10 shows that the iceberg operating system described in Chapter 7 is likely to be economically viable. A feasibility study based on technological uncertainties (the level of reliability and sustainability of the use of the studied iceberg transportation technologies) and financial aspects was undertaken. Iceberg operating research development and projects for different scales, from Antarctica to WA, cost calculations and analyses give insights on conditions of profitability of the proposed project. Iceberg harvesting may produce greater financial return than desalination technology. The conclusions of this thesis indicate a high degree of feasibility of the proposed iceberg transportation model.

11.3 Methods

The modelling of transportation systems has limitations because modelling is a schematic representation of reality (Haggett, 2001). However the multidisciplinary approach employed in developing this thesis allows identification of the fundamental characteristics of an iceberg transportation system and provides a broad analysis to support the model.

11.4 Aims and Objectives

The aim of this thesis is to identify the sustainable conditions and to assess the feasibility of an icebergs freshwater transportation system from the AAT to WA. The conditions for a sustainable iceberg transportation system have been reviewed. The sustainability and the feasibility depend on several parameters:

- iceberg operating critically depends on the ability to manage melting and stability issues;
- melting and stability could be controlled with an appropriate transportation system of waterbag and kites.
- iceberg transporting critically depends on the ability to minimise transportation costs. Minimising transportation costs is feasible if non-fossil energies are employed. However, these energy resources are more efficient over smaller distances (Dasgupta and Heal, 1979). From this point of view, WA is ideally located in terms of distance and maritime currents; transportation costs would be minimised with a current and kite based transportation system;
- a suitable technical model of a transportation system using waterbags and kites can be elaborated in the future;
- the cumulative environmental impacts of a transportation system with waterbag and kites were evaluated. They are minor or transitory;
- the benefits of an iceberg freshwater supply system from the AAT to WA were assessed.

The outcomes of this study on the operating and the transportation of icebergs consist of propositions for a detailed, original transportation system, an associated environmental assessment and a cost analysis. This framework could be used as a basis for further studies including development of a regulatory structure to set standards and oversee environmental aspects of iceberg harvesting and transportation, a wide range of materials modelling and experimentation related to freshwater transportation and more detailed assessments of financial feasibility. This study allowed to undertake an overall assessment of feasibility of the iceberg towing from the AAT to WA and to define a new approach different from the previous projects which have been engaged in the transportation of icebergs using traditional towing maritime equipment.

Throughout this thesis the supporting evidence of the economic and environmental analyses mean that iceberg transportation systems using natural energy to operate icebergs, could be environmentally friendly and sustainable and that strong savings could be obtained. The technological overview of a transportation system determined that it could be technically realistic while the legal studies of iceberg transportation determined in which conditions the operating of iceberg would be politically acceptable. Technical feasibility evaluations of preliminary testing are provided in the Appendix A6.

11.5 Theoretical Remarks

Transportation as a process of space management implies a global conception of the territory (Baud *et al.*, 1995). Transportation processes contribute to organise the space at different scales and structures (Merenne, 1995). “[T]ransportation is one of the solutions for a society to manage and control spatial discontinuities” (Bailly, 1995, p. 176).

In the field of Transportation Geography, iceberg transportation represents an opportunity to study alternative transportation systems, and to establish guidelines for research on transportation systems based on non fossil energies and new operating technologies. This helps us to reconsider the traditional paradigms of Transportation Geography and restate these paradigms in a broader sustainable frame (Wilson and Burgh, 2008).

The sustainable elements of the iceberg transportation system proposed in this thesis match to the new types of transportation systems defined by the Garnaut Climate Change Review as subsequently reducing emissions. According to the Garnaut Climate Change Review (p. 526):

> Transport emissions could be reduced faster and at lower cost if: (…) a range of road vehicle technologies become commercial sooner than assumed technologies are developed in the coming decades that substantially reduce emissions from aviation, shipping, rail, ancillary road transport and the residual emissions from road.

The Dictionary of Human Geography describes transportation as a complex process. As a transforming means, transportation is above all a process of creation of spaces (Merlin, 1991). Spaces and the actions related to them endorse human, moral, philosophical and political principles and values. Transportation systems based on alternative energies redefine the spaces they concern. The ecomobility concept could be appropriate to evaluate these transportation systems: the most sustainable system is the most inexpensive and the most efficient one, with the lowest energy consumption. This adds a practical component to the rationality of transportation sciences and could help relativising theoretical approaches of Transportation Geography. Transportation systems based on alternative energies redefines the duration of the transportation process. The costs are measured more in terms of energetic consumption than in terms of distance and time. The transportation system relying on renewable energies adapts its duration to the natural cycle of these energetic resources.

11.6 Outcomes and Future Research

My research on icebergs operating and transportation systems has several outcomes for iceberg transportation research:

- it provides an original, detailed model of a sustainable transportation system and related investigations into environmental assessments, regulatory structures and cost analysis scenarios. This approach is different from the approach taken in previous projects which were based on iceberg transportation using traditional marine towing equipment. My iceberg operating models have multiple physical, environmental, social, educational and economic aspects which can help to define future research;
- this model is sustainable in terms of techniques in respect to ecosystems and environments;

- undertaking such a project would help to initiate solutions to maintain and restore freshwater supply situation in WA. This would lead to a more sustainable development of human activities and ensure more general well being and prosperity of Australia and Australians (Pini, 2004);
- the freshwater obtained from iceberg harvesting would be a perennial, natural, maritime freshwater resource. The icebergs melted freshwater would help to solve the increasingly stressed land freshwater resources situation, by improving it in terms of quality as well as quantity. It is a transfer of freshwater volumes in the different steps of the freshwater cycle;
- this project could appeal to the general public and media. The socio-cultural image of iceberg transportation could be studied;
- iceberg harvesting may generate greater financial returns than desalination technology. Iceberg observation activity might be attractive to students of the SCAR "International Antarctic Institute";
- this project could involve the education of students to receive different academic degrees from BSc to PhD;
- the transportation system model, the environmental assessment protocol recommendations, and the legal propositions of this thesis could by submitted as patents.

My work on iceberg transportation systems and freshwater supply to different destinations creates a new level of multidisciplinary understanding. Table 11.1 gives the operational description and the corresponding timing for icebergs freshwater transportation from Antarctica to WA and/or other countries.

Table 11.1 Operation and Timing for Icebergs Freshwater Transportation from AAT to WA

Milestones	Operations	Description	Timing
1	Selection of an "ideal iceberg"	Detection and selection of a tabular iceberg, elliptical section, without cracks	Several days
2	Iceberg modelling	Iceberg's physical properties (geometry of a variable volume, gravity centre and axis)	Several days
3	Permanent sensing of gravity centre of iceberg and possible cracking	Security reasons for humans and equipment. Melting sensing	Permanent
4	Bag construction over iceberg	Auto supporting structure Peripheral circulation: for humans, maintenance, materials, equipment, storage	Several days
5	Iceberg's wrapping with an internal filet	Protection against mechanical destructive waves' action, degradation, cracking, with a filet which enhance iceberg's stability	Several days
6	Iceberg wrapping with an iceberg bag	Insertion of metallic net and protective structure	Several weeks
7	Collar attachment to iceberg's bag, on the floating line	Auto supporting structure Melted water storage, and iceberg stabiliser	Several days
7	External netting and iceberg system transportation		Several weeks
8	Melting of iceberg and collection of freshwater in a collar	Collection of the melted water into the iceberg bag collar. Devices for melting acceleration	Several months
9	Empty waterbags connexion to the collar	Empty waterbags stored in special parking and transported to the connexion stands	Several days
10	Fill-up of the waterbags	Fill-up the water bags with fresh melted water	24 hours for a waterbag
11	The links	Disconnecting of the water bags from the collar.	Two days
12	Train of waterbags	The train would be composed from 10 rows of three links.	One day
13	Kite attachment to the train		One day
14	Sustainable transportation of the train with the maritime currents		Several weeks

The model of icebergs operating and transportation systems described in the thesis can serve as a basis to experiment and develop the materials for an application for a sustainable iceberg water transportation system form Antarctica to WA. These elements would need testing to validate the calculations and the potential applications to give a more practical insight. Table 11.2 describes different experiments necessary for the proposed technology for icebergs freshwater transportation, laboratory experiments and field experiments.

Table 11.2 Proposed Laboratory Tests and Field Experiments

Operation	Laboratory tests	Field experiments
Wrapping the iceberg with a megabag	Simulation, experiments	Real scale
Assembling the collar, the internal net and the mega bag	Simulation, experiments	Real scale
Iceberg behaviour during melting	Simulation, experiments	Real scale
Collar behaviour during water transferring process	Simulation, experiments	Real scale
Bag behaviour during water transfer, connection into the train, and transportation	Simulation, experiments	Real scale
Kites behaviour during train navigation		Real scale
Bags behaviour at destination		Real scale
Bags reutilisation	Experiments	Real scale
Materials Testing for: Collar, Megabag, Waterbags, Kites	Experiments	Real scale

The experiments would consist of undertaking testing on scale models with corresponding physical characteristics of the materials (Murphy, 1979). Experimental protocols to test this project are proposed in Appendix 6. The first laboratory experiment would concern the stability of the melting bagged iceberg. Further laboratory experiments would concern the stability of the transportation iceberg bags. The elements, principles and conditions of the associated experiments are explained in Table 11.3.

Table 11.3 Iceberg Operating Experiments Elements, Scales, Principles and Conditions

Elements	Real scale model in m			1/1,000,000 scale model in m			Principles	Conditions
	Length	Width	Depth	Length	Width	Depth		
Iceberg model	200	100	50	2	1	0.5		
Iceberg foam protection bag model	600	50	1	6	0.5	0.01		
Collar	600	50	30	6	0.5	0.3		
Megabag and net	500	180	1	5	2	0.01	Experiments under different conditions of wind and currents speeds and temperatures, salinity	Test basin
80 waterbags	100	15		1	0.15			
Kites	50 m/10 m 5,000 kW. power			0.1 to 4 m/s towing simulation				
Currents power	Currents power 3 m/s							

11.7 In Situ Experiments

Using the results of the laboratory experiments, the material could be developed. The next stage would be to test the laboratory results in situ, with a detailed logistic support, remote sensing tools, extensive funding and scientific multidisciplinary collaboration. Prescriptions on the scales of these in situ experiments have been given. The logistic support required for in situ experimental projects is composed of remote sensing materials, an ice breaker research ship, a helicopter, ROV, vehicles, bags and iceberg operating materials and kites. Sensors, new materials, information and expertise would be necessary to test the decay and the stability of an encapsulated iceberg and the behaviour and the drift, of a transported waterbag or a transported freshwater waterbag train. In 2011 Providice a new venture undertook a concept development phase to study iceberg trains and single iceberg towing projects, using synchronized aluminum sails, insulation, a plastic skirt, a carbon fiber hairnet arrangement, and a towing force analysis under dynamic towing loads software. The company aims to (ProvidIce, 2011[3]): "combine three essential characteristics required for a successful improvement deployability (ease of handling before, during, and after deployment), adaptability (to the full range of iceberg sizes) and compatibility (with the existing equipment and procedure)". In situ experiments are planned (Figure 11.2).

Figure 11.2 Providice Project (credit ProvidIce, 2011)

11.8 Funding

These studies may be used by private companies or by Australian public institutions for the implementation of a system to supply the iceberg renewable freshwater resource. Australia faced serious temperature rise and significantly rainfall reduction during the last decades. CSIRO have predicted over the next 50 years that the rainfall in Australia will drop and the average temperature will rise significantly. Land freshwater resources are over polluted and over operated. Iceberg transportation is relevant for Australian freshwater supplies in terms

[3] http://providice.com/acc-1.html

of volumes. Australia has a sophisticated modern economy, with a government aware that innovation is imperative to secure its future prosperity (Cribb, 2005; Turnbull, 2006). In 2004, the Council of Australian Governments signed the National Water Initiative. Natural resources policy structures for water are shown in Figure 11.3.

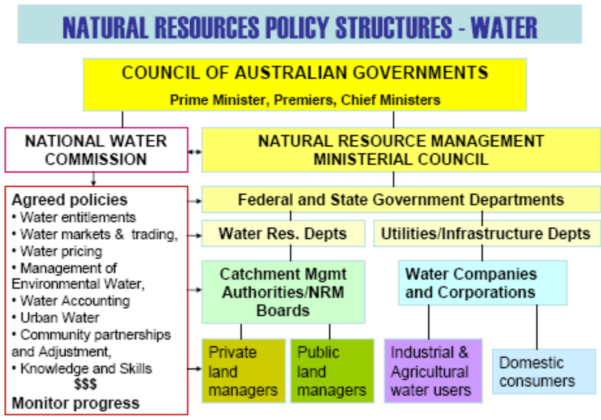

Figure 11.3 Water Resources Policy Structures, in Australia[4] (credit NWC, 2006[5]; Chartres, 2006 n.p.)

The Australian water policy is a collaboration between the Commonwealth, states, local government and the private actors. The National Water Commission goal is to measure the success of the States in meeting their National Water Initiative commitments. The Australian Water Fund is a funding program which supports the creation of water infrastructure in agreement with the objectives of the National Water Initiative. Logistic and financial support could come from national agencies such as ARC/AAS Australia, PROANTAR Brazil, BMBF and DFG Germany, NERC UK, NSF, USA, as well as Space Agencies (ESA, CSA and NASA). Water transportation companies might be interested in investing in the development of a sustainable iceberg system. A team of experts could undertake technical, environmental, financial and legal analyses. An iceberg transportation project centre could be created to coordinate and manage the operations of iceberg transportation.

Transportation Geography is not the simple description of technical performances. Transportation is a development mean. There is a human reflexion behind transportation, with appropriate systems, scales and technologies. This is the area of development of new transportation systems such as iceberg water transportation.

[4] National Water Resources (NWR) National Water Initiative (NWI)
[5] http://www.nwc.gov.au/www/html/2352-national-water-commission-act-2004.asp

Appendix 1 Water Demand in the World

The map of water demands is very complex. A balance between natural and cultural criteria must be established. Water demand depends on the accessibility of freshwater resources and on the needs of a society. However, the legitimacy of water usage will not be deliberated in depth here other than through a global presentation of the debate. I will study the environmental, demographic, social, political and economical components of the demands, uses and needs.

A1.1 Values Use and Demand

According to Smith (1776) water is a free good, and has no cost. It is worth of consideration the famous image of water and diamond presented in his book "*Treaty on the wealth of nations"* published in 1776. Water is useful as indispensable for life, but on the contrary, the diamonds as precious stones are useless for everyday life. The diamonds are expensive because they are rare. This theory reflects only an aspect of the complexity of natural resources. First water is a unique natural resource impossible to be substituted even if it is renewable: stocks are limited so the situation described by Smith has changed. Water rarity is determined by the water uses. Water value for the future generations is hard to determine as it is not defined (like other natural renewable resources) by a simple consuming value, but by its availability and uses such as its relative value for drinking potable uses, irrigation, cleaning, cooling industrial uses, hydroelectric power, environmental, or recreation. Water is used in economic activities According to the UNESCO (2010[1] n.p.) "Water has an economic value in all its competing uses and should be recognized as an economic good". Water value (Bontoux, 1993) is a function of multiple factors (related to uses). The energetic value of water is composed of its uses:

- the physical and chemical properties of water;
- the thermal properties, which explain temperature stability in oceanic climates;
- the energetic value;
- the hydraulic value.

An organic value of water composed of:
- the biological value for living organisms;

[1] http://www.unesco.org/water/wwap/facts_figures/valuing_water.shtml

- the ecological value - as aquatic biotope;
- the absorption and storage of CO_2 in oceans;
- the symbolic and aesthetic value.

These characteristics interact. The water value is directly referring to consumers' style of life. The demand of water is a function of human behaviour. The market mechanism plays an important role in reallocating resources from lower valued to higher valued uses (Jordaan, 1999). In the near future this will maybe be the case of icebergs in supplying freshwater. However, success of water marketing will depend on a combination of economic, legal, institutional, environmental and technical factors. Freshwater environmental, demographic and industrial uses are expressed in terms of quantity, quality and accessibility of consumptions, and by extension of needs and values. The potential economic gains from water trade will motivate water transfer from lower value to higher value uses.

A1.2 Water Consumption and Access

Water needs for humans is covered with by less than 0.0005% of the Earth's water resources (5,000 km^3). This represents an average of 1,300 m^3/year/person or more than 2 m^3/day/person (Figure A1.1). This amount could double in the next 50 years. However while the wealthiest persons consume over 5,000 m^3/year/person, the poorest live with 10 m^3/year/person, 30 l/day/person. People already use over half the world's accessible freshwater, mainly land freshwater, now, and may use nearly three-quarters by 2025.

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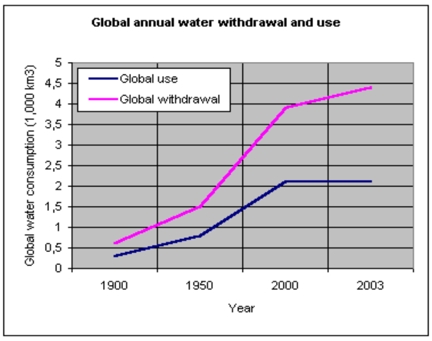

Figure A1.1 Global Annual Water Withdrawal and Use (credit Lenntech publications[2] 2003, n.p.)

[2] http://www.lenntech.com/specific-questions-water-quantities.htm, http://www.blueplanet.nsw.edu.au/templates/blue_content.aspx?edit=false&pageID=518

This water access determines the direct types of consumptions and tradability. The accessibility to water is expressed by direct and indirect factors related to the water consumptions of individuals and societies determined by physical (climatic and environmental) demographic and cultural conditions of the water users (Encyclopedia Universalis, 2003). The system of consumption in the world depends on resources access and needs from human activities and on water supply networks. Therefore, water consumption also varies with demography, climate, and the nature of human activities, ages, and life styles. The figures of water consumption reported in the literature are very heterogeneous, being expressed in different units of measurements. Their definition is not precise and is not normalized. For this reason it is difficult to compare the situation related to water consumption and access in different countries. The average numbers do not reflect the density of the real situation. In 2006 the total renewable freshwater supply is about 50,000 km^3/year. It is generally stated that African countries have a low water consumption (around 100 m^3/inhabitant/year mainly are used for agriculture, when the consumption for individuals do not exceed 10 m^3/inhabitant/year). Western countries have an average consumption of 1,600 m^3/inhabitant/year, from which the individuals consume between 50 m^3/inhabitant/year in countries which recycle a lot of water, and 500 m^3/inhabitant/year in countries which waste a lot of water, such as USA and Australia. The main part of the consumption covers industrial needs. Generally, the Middle Eastern countries consume 500 m^3/inhabitant/year for individuals and agriculture but less for the industries. Latin American and Asian countries have a higher consumption for agriculture (especially for demographic reasons) and a growing consumption for industries (around 500 and 1,000 m^3/inhabitant/year). By 2025, 5,100 m^3/person will be available for human use, for an eight billion global projected population, two times less than in 1990 (Lenntech publications). The access to safe drinking water in 2008 is shown in Figure A1.2.

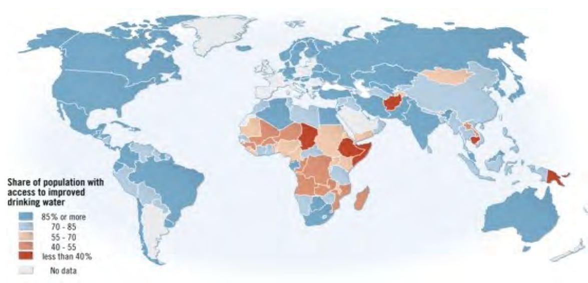

Figure A1.2 Access to Safe Drinking Water (credit Ahlenius, 2008[3] n.p.)

[3] http://maps.grida.no/go/graphic/access-to-safe-drinking-water

The Middle East and South East Asia countries will face the biggest stress. Additionally, in regions of Africa and Asia a short term crisis could be expected before efficient networks are developed. Gleick (1996; 1998[4]) evokes a fundamental human right to having access to water. This would equate to 50 l of water per day/person, 20 m^3/person/year and would be composed of:

- 5 l/day/person for drinking water;
- 20 l/day/person for sanitation services;
- 15 l/day/person for bathing (30 second shower);
- 10 l/day/person for food preparation.

According to Diop *et al.*, (2008[5]):

> According to Population Action International, based upon the UN Medium Population Projections, more than 2.8 billion people in 48 countries will face water stress, or scarcity conditions by 2025. Today, 31 countries, accounting for less than 8% of the world's population, face chronic freshwater shortages. Many African countries are facing serious water shortages. Parts of other large countries (e.g. China) already face chronic water problems (Hinrichsen *et al.,* 1998; Tibbetts, 2000). - Bahrain, Kuwait, Saudi Arabia and the United Arab Emirates have resorted to the desalinization of seawater from the Gulf. Bahrain has virtually no freshwater (Riviere, 1989), while three-quarters of Saudi Arabia's freshwater comes from fossil groundwater, which is reportedly being depleted at an average rate of 5.2 km^3 /year (Postel, 1997).

Ethiopia, India, Kenya, Nigeria and Peru will face a water crisis in the next 25 years (Falkenmark, 1989[6]) as well as regions of west Asia, North Africa or sub-Saharan Africa. By 2050, up to four billion people out of a total world population of 9.4 billion people could be in a water scarcity situation. It is generally admitted that a water crisis results from the lack of short term available resources (Table A1.1).

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[4] http://www.pacinst.org/about_us/staff_board/gleick/gleick_publications.htm, http://books.google.com.au/books?id=MR3gjLbcmVIC&printsec=frontcover#v=onepage&q&f=false
[5] http://www.unep.org/dewa/vitalwater/article141.html, see also http://www.tau.ac.il/~ecology/virtau/8-manal/postel.pdf
[6] http://onlinelibrary.wiley.com/doi/10.1111/j.1477-8947.1989.tb00348.x/abstract, see also http://itia.ntua.gr/hsj/42/hysj_42_04_0451.pdf

Table A1.1 Sanitary Access in the World

Sanitary Access in the World (in millions of persons and %)				
Regions	**Populations with access**		**Populations Without Access**	
North Africa and Middle east	190	60%	150	40%
Africa	190	30%	420	70%
Europe	490	96%	15	10%
North America	380	97%	10	5%
South America	320	60%	220	40%
Asia and Pacific	1,950	52%	1,850	48%
Total	2,550	60%	2,650	40%

80% of the illnesses registered in water scarce countries are directly related to the water quality and scarcity. The absorption of contaminated waters induces poliomyelitis, malaria, cholera, typhoid fever, dysentery or hepatitis. These illnesses are responsible for the deaths of 34,000 persons/day. The World Health Organization, WHO (1995) estimates the morbidity (episodes/year) and the mortality (deaths/year) of water related diseases (Table A1.2).

Table A1.2 Estimates of Morbidity and Mortality of Water Related Diseases (credit WHO, 1995[7] n.p.)

Disease	Morbidity (episodes/year)	Mortality (deaths/year)
Diarrheal diseases	1000,000,000	3,300,000
Intestinal helminths	1,500,000,000	100,000
Schstosomiasis	200,000,000	200,000
Dracunculiasis	100,000	-
Malaria	400,000,000	1,500,000
Dengue fever	1,750,000	20,000
Poliomyelitis	114,000	-
Trypanosomiasis	275,000	130,000

A1.3 Direct Water Consumption

Direct water consumption is composed of the demand for human living and industrial activities. These activities are defined by the level of technology developed to transport and supply them in water resources. In 2007, mankind needed more than 5,000 km^3, which is about 2 m^3/person/day, from which 60% for irrigation, 30% for industries and 15% for daily needs of individuals (0.3 m^3/day/person). 70% of the water is transported through hydraulic means of transportation for agriculture, 22% for industries and less than 8% for domestic uses (Lenntech Water treatment & purification Holding B.V., 2008). Agriculture consumes an enormous quantity of water. Irrigation represents around 60% of the freshwater consumption in the world. Numerous civilizations developed adapted techniques to use and regulate

[7] http://www.aaas.org/international/ehn/fisheries/gleick.htm, http://www.worldwater.org/table22.htm

available water resources to their related environment. During the Antiquity, eight million hectares had been irrigated, in 1900 it is reported that 48 million hectares are irrigated, 100 million in 1950 and 270 million hectares nowadays. Today 15% of lands are irrigated (almost 100% in Egypt, 95% in Mauritania, 82% in Cambodia and 75% in Pakistan). 40% are irrigated through dams and 60% by rivers and channels. Rainwater is not counted in these statistics. However nowadays it would be very hard to reduce irrigation. The increase in population implies an increase of the agricultural production by more than 50% in order to provide food to the future generations. Different types of irrigation exist, such as: the aspersion irrigation, the immersion system with channels and holes, and the dropped irrigation (right at the base of each plant). Very old irrigation systems based were destroyed in spite of their success and their respectful use towards the environment. The building techniques of some brickworks and traditional channels are kept. Modern western technologies brought less efficient irrigation systems. A whole range of new water supply techniques combined to new networks have been designed, such as high tech dams, channels, desalination plants. For example, open irrigation systems have very low yield because water evaporates and produces increasing salinity. The best solution would be to develop sustainable technologies and to promote adapted solutions for each environment. The use of unsustainable irrigation systems destroyed the agricultural lands in Mesopotamia, which 5,000 years ago nourished the world and which in turn became deserts. The demographical pressure is strong; millions of persons are concentrated to live in small and limited spaces (densities of 100,000 inhabitants/km^2 are nowadays current common). By 2025 the urban population will have increased by 160%. Two thirds of the world population will be living in cities compared with 50% nowadays. According to some studies of the Scripps Institute of Oceanography, San Diego, lands could lose around 1,800 billion m^3 of water because of wild urbanisation and impermeable roads buildings which could result in a 5 mm increase of the ocean levels. Industrialisation, urbanisation and intensive agricultures gave rise to an important deterioration in terms of water quality in developing countries. Urbanisation also increases the technical and commercial costs of water supplies.

A1.4 Direct Consumption Water Crisis

Statistical studies (Rosengrant *et al.*, 2002) have shown that every year there are 85 million more persons more to nourish and supply with water and goods. In addition, the water consumption doubles every 20 years, which is two times faster than the population is increasing. The world consumption had been has multiplied by 35 since 1750, by seven since 1900 and by two since 1980. In the 1980s, problems of chronic droughts appeared more seriously in arid countries, which involved 40% of the world population. In the last 25 years, we have seen a decrease of water availability per person by 33%. Seventeen countries have drastically exhausted their water cycles systems and 47 countries are in a moderate stress.

Based on population and water availability projects, the countries are classified as:

- water stressed countries (between 1,700 m^3 and 1,000 m^3/capita), in which case water supply problems tend to become chronic and widespread;
- and water scarce countries (below 1,000 m^3/capita).

Water shortages can jeopardise economic development and affect severely environments. In 2005 water stressed countries were: Cameroon, India, Nigeria, Peru, Poland, Uganda, Tanzania, and the UK. The water scarce countries are Algeria, Burundi, Comoros, Ethiopia, Iran, Kenya, Gaza, Malawi, Morocco, Rwanda, South Africa, and Tunisia. Large inequalities are observed depending on the mastering of the resources (drought and flood treatments), even in the most tempered regions.

The issue is therefore to promote technical breakthroughs to make the water access more rational, cleaner, easier, larger, and to ameliorate the sharing conditions. The issue is to develop flexible, sustainable and cheaper means of transportation. First of all it is necessary to define the regions which have the biggest needs and those which do not have large economic capacities. According to Figures A1.3a, and b, water supply networks have to be developed in Asia and Africa. The environmental values of water are also growing, increasing the scarcity of the resource.

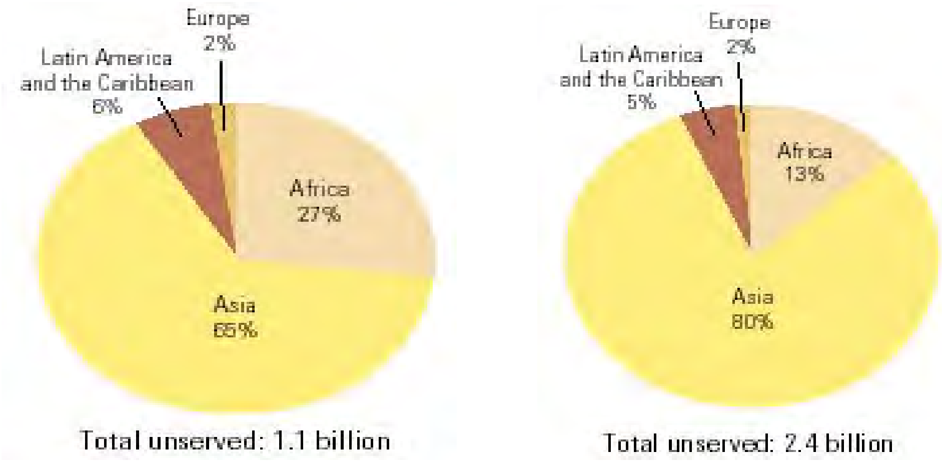


Figure A1.3a Water Supply, Distribution of Unserved Populations (credit United Nations Educational, Scientific and Cultural Organization UNESCO, 2003 n.p.)

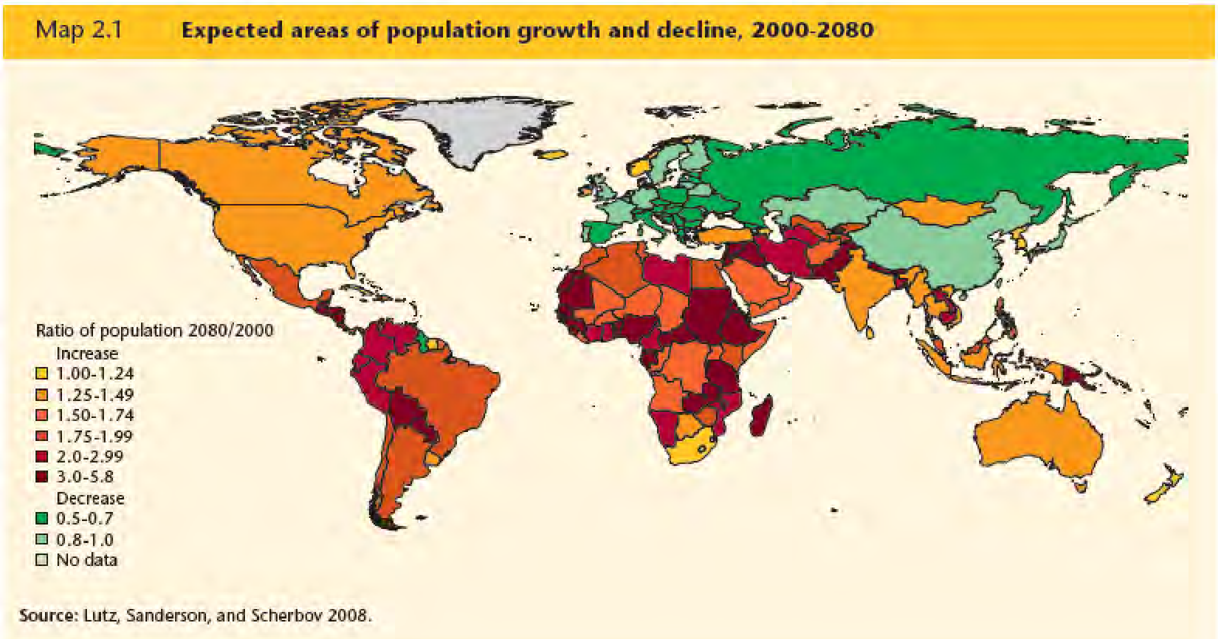


Figure A1.3b Populations Growth 2000 2080 (credit UNESCO, Lutz, Sanderson and Scherbov, 2008[8] p. 4)

A1.5 Environmental Values of Water

Water is a vital resource for human, animal and plant health. Water bodies provide habitats for aquatic life and riparian systems provide moisture for vegetation and terrestrial biota,

[8] http://www.unesco.org/water/wwap/wwdr/wwdr3/pdf/WWDR3_Facts_and_Figures.pdf

transporting nutrients between one ecosystem and another (Gleick *et al.,* 2002). Water is a renewable resource available through natural hydraulic cycle of the atmospheric-oceanic-terrestrial system. Large-scale withdrawals or transfers of water can change ecological conditions and thus the in situ benefits of a water body. The environmental economy is based on the interactions between the goods analysis and the access rights. The environmental value of water can be defined with the hedonist cost method which is based on the value of the goods (Vallée, 2002). An ecological price of water should be rationally established. Nevertheless the evaluation of the damages caused by human pollution on the natural resource is complicated. Iceberg case has to be considered in this perspective in its limited maritime resource frame integrated into the water economy. The demands for water express a part of the environmental needs of human societies in an indirect form.

A1.6 Indirect Water Consumption

Indirect water consumption is determined by the natural local water cycles for each environment. The natural and climatic inequalities are as problematic as the demographical and technological ones. Different ecosystems have different water needs. Tropical, arid countries and islands suffer the most; some countries will have bigger environmental needs than others. In 2007 UNESCO had defined 529 biosphere reserves programs in 105 countries. (Figure A1.4).

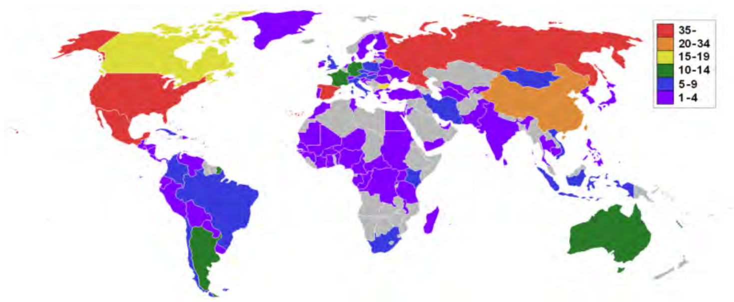


Figure A1.4 The Biosphere World Network of Biosphere Reserve (credit Karlstrom, UNESCO, 2007[9] n.p.)

As a result of the dry Australian climate, water supplies are extremely important for the Australian environment. In Australia the biosphere reserves are the followings:

[9] http://sites.google.com/site/waterwatchalliance/agenda21

- Croajingolong National Park from1977;
- Kosciuszko National Park, from1977;
- Île Macquarie, from 1977;
- Regent Prince River, from 1977;
- Southwest, from 1977;
- Unnamed, from 1977;
- Uluru (Ayers Rock - Mount Olga), from 1977;
- Yathong, from 1977;
- Fitzgerald River, from 1978;
- Hattah-Kulkyne & Murray-Kulkyne, from 1981;
- Wilsons Promontory National Park, from 1981;
- Bookmark Biosphere Reserve, from 1977, extended 1995.

Biospheres and the biodiversity of their ecosystems are important for the functioning of land water systems. They are under a growing stress and require measures of protection, maintenance and restoration. The countries with important biosphere reserves generally allow a significant part of their water resources for the protection of these regions. To meet human demand, during the 20th century, all over the world, the water policies relied on the development of massive infrastructures (dams, aqueducts, pipelines, etc) and elaborate centralized treatment plants, for the benefit of billions of people. On the other hand the infrastructures had enormous costs and generated unexpected social, economical and ecological problems. Large populations have been displaced by water projects (World Commission of Dams, WCD, 2000[10]). At the same time partial extinctions of freshwater fauna populations are observed. "Water, nutrient and sediment fluxes in river basins are shown to be highly impacted and regulated by humans through land use, pollution and river engineering" (Kabat, 2003[11] p. 1). Pacific Institute USA reports losses of habitat and depletion of native fish in deltas of many rivers (Nile, Danube, Amu Darya, Syr Darya, Colorado), plummeting population of birds or shoreline erosion. In this context water demand can be estimated as real or ideal consumption criteria and standards. These two approaches contain an assumption which needs debating: "Should water demands be measured through an ideal life style, egalitarian and authoritative or through particularities of life styles corresponding to the environmental and climatic geographical systems?" MEDCs have designed distribution networks, can afford high prices and negotiate large supplies, own

[10] http://www.dams.org/report/reaction_irn.htm
[11] http://128.138.136.5/science/groups/pielke/classes/at711/bookflyer.pdf

resources, achieved demographic stability and benefit from the best technologies of environmental resource management and recycling industries. They are creating sustainable water networks which allow them to supply water at a relatively cheap price particularly as their consumption will remain quite stable. On the contrary, the emerging countries such as China or the Persian Gulf countries, having high population densities, a high economical growth rate and reduced water supplies, are willing to afford water consumption at a higher price. They developed their water resources (with improved water management, recycling, desalination and large scale dams), despite environmental damage (ecological sacrifice).

A1.7 Water Resources

I analysed the location of the water resources and the costs of the different water transportation and supply techniques. Water is a renewable resource. The water cycle is very complex and its rhythm is a function of the interaction between climates, man and the environment. Table A1.5, Figure A1.6 and Figure A1.7 show the annual renewable water resources all over the world. The distribution of the world's freshwater resources is shown in Figure A1.8. There are inequalities in terms of location, extraction and distribution, which correspond to the levels of development and demographic, environmental and social values uses and needs (Dabney *et al.*, 2003). These are clearly revealed when comparing the map of the Figure A1.5, A1.6 and A1.7, as the freshwater resources per river basin illustrate the environmental needs, while the map of the regional resources integrate them, focusing on the availability for direct consumptions.

Table A1.3 World Water Availability (credit "Looking south: Managing Technology, Opportunities and the Global Environment" Academy Symposium, November 2001[12] n.p.)

Region	Annual renewable (km^3)	Withdrawal quantities (km^3)	Availability in%	Year
Africa	3996	145	A1.6	1995
Europe	6234	455	7.2	1995
North America	5309	512	9.6	1991
Central America	1057	96	9.1	1987
South America	9526	106	1.1	1995
Asia	13206	1633	1A1.3	1987
Oceania	1614	17	1.1	1995
Australia	343	19	5.5	2000
Antarctica	3250	0	0	2000
World	43022	3240	7.9	1987

[12] http://www.atse.org.au/index.php?sectionid=326

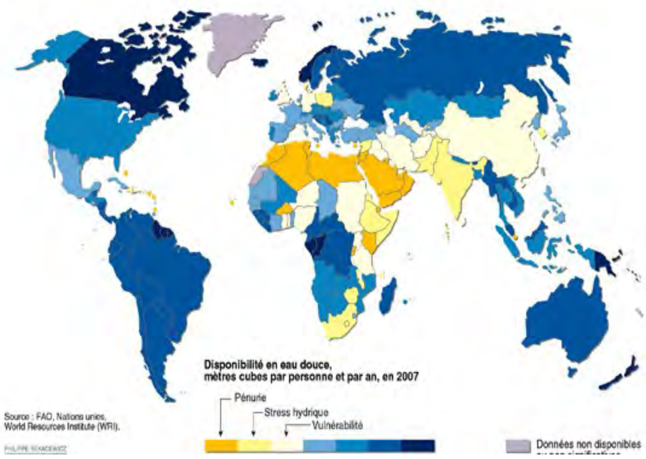


Figure A1.5a Annual Renewable Freshwater Availability in m^3/capita/year in 2000 (credit Rekacewicz, 2008[13] n.p.)

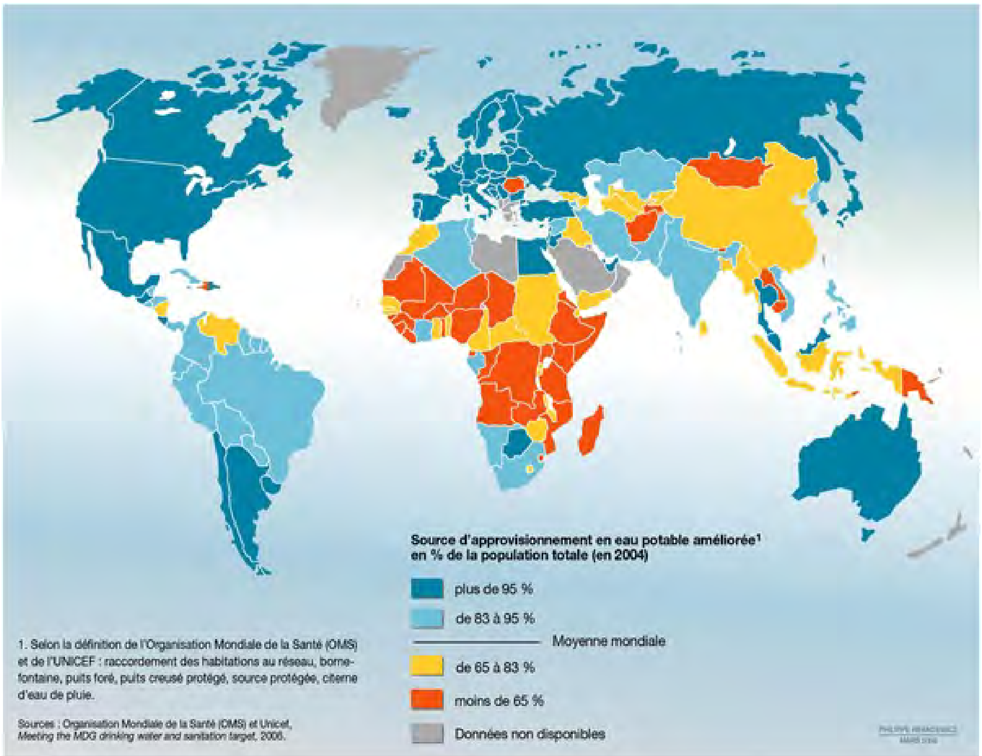
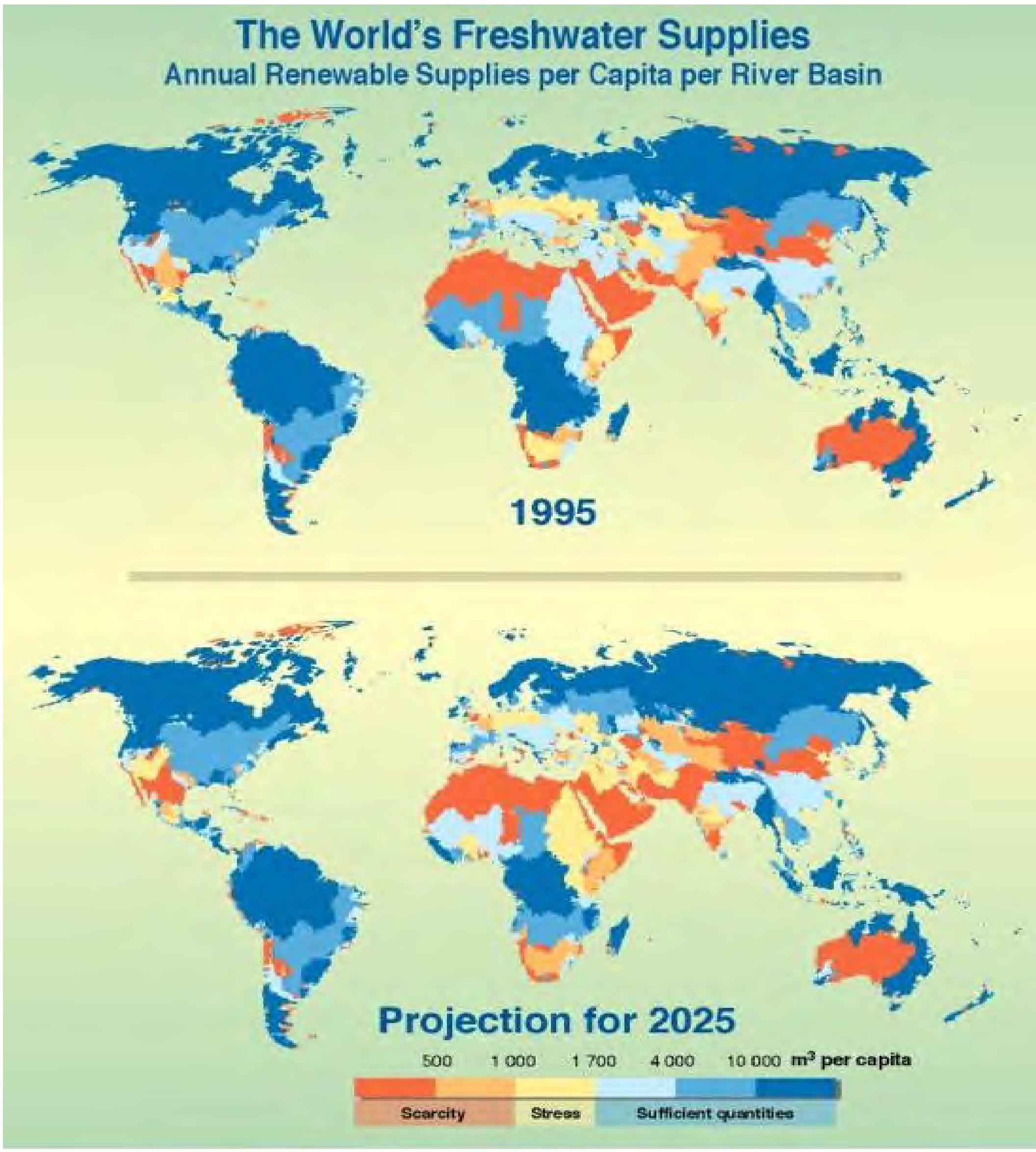


Figure A1.5b World Map of Drinking Water Access in 2006 (Rekacewicz, 2009[14] n.p.)

13 http://maps.grida.no/go/collection/vital-water-graphics
14 http://maps.grida.no/go/graphic/total-population-access-to-an-improved-water-source



	m³ per capita per year		m³ per capita per year		m³ per capita per year
North America		**Europe**		**Asia and Australia**	
1 Yukon	1 249 832	25 Danube	2 519	13 Volga	4 260
2 Mackenzie	408 243			14 Ob	14 937
3 Nelson	15 167	**Africa and West Asia**		15 Yenisey	79 083
4 Mississippi	8 973	8 Niger	4 076	16 Lena	161 359
5 St. Lawrence	9 095	9 Lake Chad Basin	7 922	17 Kolyma	722 456
		10 Congo	22 752	18 Amur	4 917
South America		11 Nile	2 207	19 Ganges and Brahmaputra	-
6 Amazon	273 767	12 Zambezi	-	20 Yangtze	2 265
7 Paraná	8 025	26 Orange	1 050	21 Murray Darling	-
		24 Euphrates and Tigris	2 189	22 Huang He	361
				23 Indus	830

Source: Revenga et al. 2000, from Pilot Analysis of Global Ecosystems: Freshwater Systems.

Figure A1.6 Renewable Freshwater Supplies, Per River Basin (credit Revenga *et al.*, 2000[15] n.p.)

[15] http://maps.grida.no/go/graphic/renewable_freshwater_supplies_per_river_basin

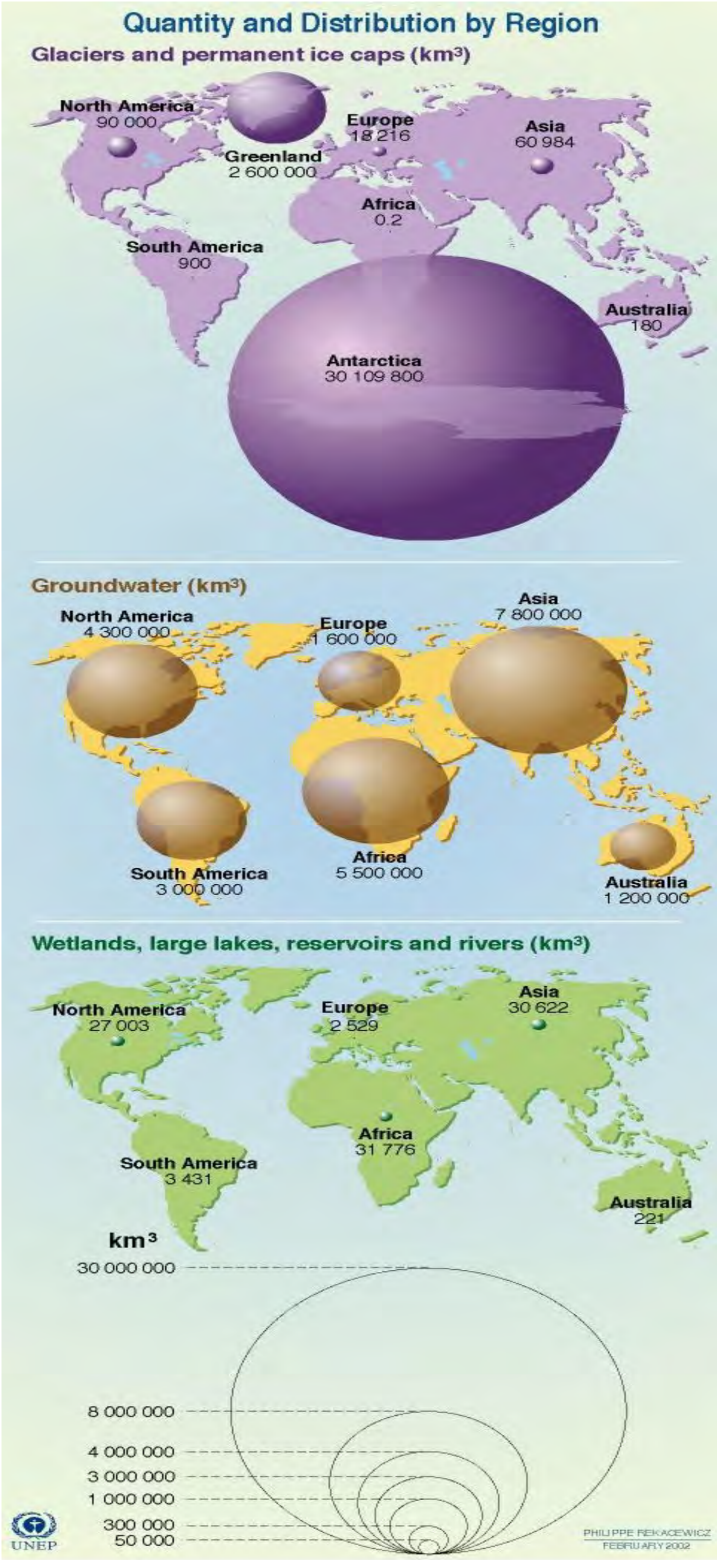


Figure A1.7 Distribution of the World's Freshwater Resources (credit Shiklomanov, UNESCO, 1999[16] n.p.)

16 http://maps.grida.no/go/graphic/global_freshwater_resources_quantity_and_distribution_by_region

Nine countries (Brazil, Russia, the United States (with Alaska), Canada, China, Indonesia, India, Columbia and Peru) share 60% of the usable renewable freshwater resources of the world (Gleick, 1993). Brazil possesses 20%, Russia 10.6%, China 5.7%, Canada 5.6% (yet China's population is 30 times larger than Canada's). On the other hand some countries such as Kuwait, Bahrain, Malta, Gaza, United Arab Emirates, Saudi Arabia, Singapore, Libya, Jordanian, Israel, and Cyprus have very limited freshwater resources, less than a few million m^3/year (UNESCO, 2003). Observing the Earth one can see strong inequalities in matter of land freshwaters (Chalecki and Gleick, 1999; Table A1.5). The available quantity of freshwater per inhabitant is less than 500 m^3 in Kuwait, Malta, Saudi Arabia and Libya. The quantity of freshwater per inhabitant is more than 100,000 m^3 in Iceland, Norway, Cambodia, Canada and New Zealand. The countries with water scarcity have < 1,000 m^3/person/year; the countries with water stress have between 1,000 and 1,700 m^3/person/year; the countries having sufficient water have > 1,700 m^3/person/year. The average poverty level of water per country is generally established around 1,000 m^3 in the world. In Europe and in Australia, this threshold is much higher, namely 2,500 $m^{3.}$ The driest regions are located in Australia, Africa, the Middle East, Asia, north and South America (Figure A1.6). Some of these regions are far from regions with freshwater resources. This is the case in Australia, the Middle East and Central Asia. Very little resources are available in North and West Africa, the Middle East, India and China. Asia, Central America, the Middle East and Australia will be significantly over the average by 2050. Regions in North Africa, the Middle East, Central Asia, India, South East Asia, Europe, North America, and Australia will face shortage of water supplies as the supplies are decreasing. Europe and Asia have limited resources in surface waters. The situation in Africa does not reflect the variability of situations. However, in the African continent there are a lot of resources, the main difficulty lies in the lack of infrastructures. In Oceania, the situation seems to be comfortable. However most of the resources are not located in the urbanised part of Australia. Water resources are limited in populated areas. Water transportation techniques have different characteristics given the different resource and operational costs.

A1.8 World Water Shortage

The world water shortage explains why icebergs could and should be considered as water supply resources. For some developing countries, the simplest way to limit the costs is to limit the loss; several simple rules could save a lot of water (Madden and Carmichael, 2007; Rouyrre, 2003) but network failures and poor network supplies imply a situation of paradoxical water scarcity, for example most of the Sub Saharian African countries. In some countries with small amounts of available freshwater, efficient supplying networks and re-treatment solutions allow a good accessibility for populations. In other countries even with recycling technology and an efficient water network supply, new resources will be needed (Middle Eastern countries, south eastern Asian countries, some Sub Saharian countries, Caribbean countries, and to some extent Australia). It would need several years to be secured but the design of a reliable and sustainable system of iceberg transportation is a unique opportunity to provide global solutions the water supply network. However at an early stage, the efficiency of a system of iceberg transportation would also be correlated to the distance from the resource. Therefore the best location for iceberg water transportation would be Australia, Sub Saharian coastal countries and then South East Asia, and the Middle East with environmental or human or industrial criteria of consumption. It is hard to estimate the quantities of the future needs but based on the sizes and the populations and the culture of consumptions and the climates of the shortage regions, a volume of around 200 km^3, 20 for Australia, and 100 South East Asia, 50 Sub Saharian countries and 30 for the Middle East would be needed. The quantities available depend on several parameters. While glacier ice renewability cycle is very slow (10.000 years), the renewability cycle (years) and the icebergs resource volumes are compatible with an industrial scale supply. This scale still needs to be defined. The world's human population of six billion uses approximately 5,540 km^3 of water each year from a total annual renewable resource of some 55,000 km^3. Antarctica with about 30 million km^3 of water yields an average of 1,500 km^3 in the form of icebergs each year (which is about 22 times Australia's annual renewable water supply). A sustainable yield would be between 10 and 30% of the resource (150 to 500 km^3). Hult and Ostrander gave an estimate of the maximum development that might be anticipated for iceberg transportation (Figure A1.8)

	Millions of k·m³ or acre-ft
United States and Mexico	30
Australia	10
South America	10
Middle East	10
Africa	10
Japan and West Pacific Islands	10
Maximum estimated total by year 2000	80

Figure A1.8 Estimate of the Development for Iceberg Transportation (Hult and Ostrander 1973[17] p. 9)

[17] http://www.rand.org/pubs/reports/2008/R1255.pdf

A1.9 International Problems

Undoubtedly the most serious unsolved water problem is the failure to meet basic human needs for water (Gleick 1997[18], 1999; 2000; 2003). More than one billon people lack access to safe drinking water worldwide (WHO, 2000; Flakenmark, 1997). Gleick (2003[19] p. 1525) noted "[U]ltimately, meeting basic human and ecological needs for water, improving water quality, eliminating overdraft of groundwater and reducing the risks of political conflicts over shared water require fundamental changes in water management and use." The sustainability criteria for sustainable water planning and management, as defined by Gleick (1998) are:

- basic human requirements;
- basic environmental water requirements;
- water quality international standards (ISO standards, depending on location and on the way in which water is used);
- renewability of freshwater resources;
- data collection and resources availability (made accessible to all parties);
- institution, management and conflict resolution (institutional mechanisms will be set up to prevent and resolve conflicts over water with democratic decisions).

Through an interesting comparison with oil, he analyses the concept of peak water (Table A1.4). This targets the future water stressed countries and allows to determine the means of actions that they will need to develop. If improving water network policies and technologies is a priority, developing efficient means of transportations will be a necessity as well.

Table A1.4 Oil and Water: Selected Characteristics Answering Some Questions (Gleick *et al.,* 2009[20] n.p.)

Characteristic	**Oil**	**Water**
Quantity?	Finite	Literally finite, but unlimited (at a cost)
Renewable or Non Renewable?	Non renewable	Renewable, but with locally non renewable stocks
Transportability?	Long distance transport economically viable	Long distance transport *not* economically viable
Substitutability?	Wide range of alternatives can substitute	No substitutes for most purposes

[18] http://unu.edu/ona/PDF/Papers/Gleick,%20Peter%20PAPER.pdf
[19] http://www.atmos.washington.edu/~earth/earth3/gleick.pdf
[20] http://books.google.com.au/books?id=_wd-s1FB7VEC&printsec=frontcover#v=onepage&q&f=false

Water management together with climate change are challenges that face the humans in the 21st century (Alcamo *et al.,* 2000). The physical, economic, social and political characteristics of water make it a unique resource in which a degree of government involvement is inevitable. Modern water systems are international and don't respect regional boundaries. In Europe for example, the Danube River crosses 17 national jurisdictions. "In the EU the development of the Water Framework Directive is a watershed, because it allows each member states to have a consistent and concerned approach to water management while allowing for their unique contexts" (Hussey, 2007). The European Union Water Initiative is based on four pillars: reinforcing political will for concrete action, improving coordination, and increasing efficiency and water governance for long term sustainability (Paglia, 2007; SIWI Stockholm International Water Institute[21]). Similar approach is done in Canada and South Africa. In their regulatory approach the US suffer and benefit from severe fragmentation across states. The case of California is discussed by Hanak (2007). The modern water planning approach is focused on a portfolio of options including non-traditional sources such as recycling, desalination, underground storage, cloud seeding and, more efficient use of existing supplies, such as conservation and water marketing. For China and India water regulation and management is a challenge. China has problems related to the over-extraction of groundwater. Overdraft of groundwater at a higher rate than recharge causes irreversibly damage to the aquifer, and induces saline intrusion (Rosegrant *et al.,* 2002). India has major problems with sanitation and water quality but also environmental ones. Some Middle Eastern or African countries are arid and have depleting underground water supplies. As a global resource, water would need a global harmonisation of the water policies. The United Nations agency working for human settlements launched two programs, the Global Water Operators' Partnership and Water and Sanitation Trust Fund. With the International Year of Sanitation in 2008 global attention is focused on the critical need for improved health and hygiene all over the world (SIWI, 2007). According to the World Health Organisation water consumption would have to be halved by 2025 (Hayward, 1996). Transporting water across borders becomes a major issue. Adapting costs to uses implies to have a universal standard for supply, sanitation, agricultural, industrial activities, environmental activities and recreational uses. These two last types of values may increase in the future with the development of new socio-cultural way of lives focused on non productive activities. The World Health Organization has defined for basic access 20 l/day, capita and 100 l/day as optimal access associated with low health concerns.

[21] http://www.siwi.org/

Through water pricing it is possible to improve water allocation and to encourage users to conserve scarce water resources (Dinar and Subramanian, 1997). Water market can solve conflicts within its own economical rules by establishing a price acceptable to all parties and by including the different costs and values of water supply. A more rational pricing would balance the uses and the needs for water by taking in account its affordability. However, exclusive property rights within nations (which set a specific balance between accessibility and use, costs and values, demand and offer, resources and needs) are making the pricing unclear. The source of water is generally considered as a public welfare duty, or a private service financed by taxes or fees (Saleteh and Dinar 2000; Rosegrant *et al.,* 2002). Developed agricultural industries, drinking or sanitation access are usually the cheapest activities. Mainly the water is consumed for agricultural and industrial uses. It is generally admitted that in the near future water consumption will rise and uses will change. Throughout the world, subsidies from local, regional or governmental sources finance major part of the costs. Water marketing can adjust costs to uses and act in different fields. Water market can serve as a tool for efficient allocation of water among different users. In areas where water storage exists, water marketing could be an inexpensive way to:

- reallocate water as for example in large metropolitan areas and during water shortage periods due to severe drought;
- provide and supply water for environmental and recreational needs;
- incentive action for water conservation and efficient use of natural resources;
- promote the political and social harmony among the groups with excess water supply or demand;
- counter the development of inequalities and operate sustainable projects.

Other resources than financial ones and price policy are conditioning well balanced water uses and consumptions such as educative and political ones. Water education should be promoted to encourage efficient use access and sharing of the scarce resource and to reduce wastage. On planet Earth, disequilibrium in freshwater availability exists. Only nine countries share 60% of the renewable resources of the world and on the other hand some countries have nearly no water. The water access is determined by climatic, environmental, demographic and cultural conditions of the water uses. Consequently, I focus on the water economy, and the market pricing mechanisms. Water cost for particular uses is a function of its location, accessibility, quality and timing: water is hard to transport but easy to waste. Water values also vary. They depend on demographic, socio-cultural, technical and economical factors. Water has a price of transporting. Water crises are due to the irregularity of the available resources. Large inequalities are observed. Comparing the demographical density maps, the technological development levels and the water resources, regions which will face the most serious water shortage problems are in the Middle East, in North Africa, in Central Asia; in South East Asia and in Australia water shortage will be significant as well. If human criteria are considered as a priority, then the freshwater supply must be addressed to some countries in Africa. Freshwater supply of Australia and South America could be possible because of the geographic proximity and the quantities available (Keeling, 2008). Another possibility is to consider Australia, the Middle East countries and the countries from South East Asia for their economical capacities to afford such projects. To improve this situation it is essential to discover new water sources and to promote new sustainable technologies for freshwater transportation. Water transportation could help poorer regions to reach a better balance in their water uses (McCalla, 1994). The freshwater extracted from icebergs can then be distributed to different countries following different priority criteria. The main obstacle is however political as any project of iceberg operating would need a significant political investment (Schwerdtfeger, 1986). Water regulation can serve as an economical tool for efficient allocation of water among different users. Most of the predictions claim that demographic growth will stabilize but the increasing of water volume demand and price is inevitable. Following the statistics presented in 2000, the water world consumption (about 2,800 km^3) doubles by 2010. Moreover, as the population is growing, the available amounts of water per person will be considerably reduced. The world population has multiplied by 12 in 150 years. Low estimations predict 9.5 billion human beings in the 2050s. Water needs will double by 2025. 1.5 billion persons (25% of the world population), do not have access to high-quality freshwater and more than two billion do not have a proper waste water system. It is predicted that seven billion persons (70% of the world population) from 65 countries will face a water shortage by 2050. The United Nations Organisation evaluates that 4.6 billion humans will have to be occasionally stressed with water supply in the 2050s (<1,000 m^3/year). The World Health Organization claims that the water minimal sanitary quantity is estimated to be 10 m^3/person/year, depending on climate conditions (WHO, 2000). The quantity of about 10 m^3/person/year is necessary for survival. In 1990, 131 million people had insufficient resources to live, with less than 1 m^3/person/year. The water deficit should increase by five, as in 2025, there will be 817 million in such a situation. According to the International Water Management Institute a large part of the world will suffer from both physical (1000 m^3/person/year renewable water supply) and economic water scarcity by 2025. A large majority of countries of the world will face water crisis in the coming years. Their priority will be to improve their water supply network, by developing recycling technologies and sustainable water uses. New water resources and transportation techniques must be developed at the same time in the near future. Figure A1.9 synthesises the factors which will determine water crisis in the future.

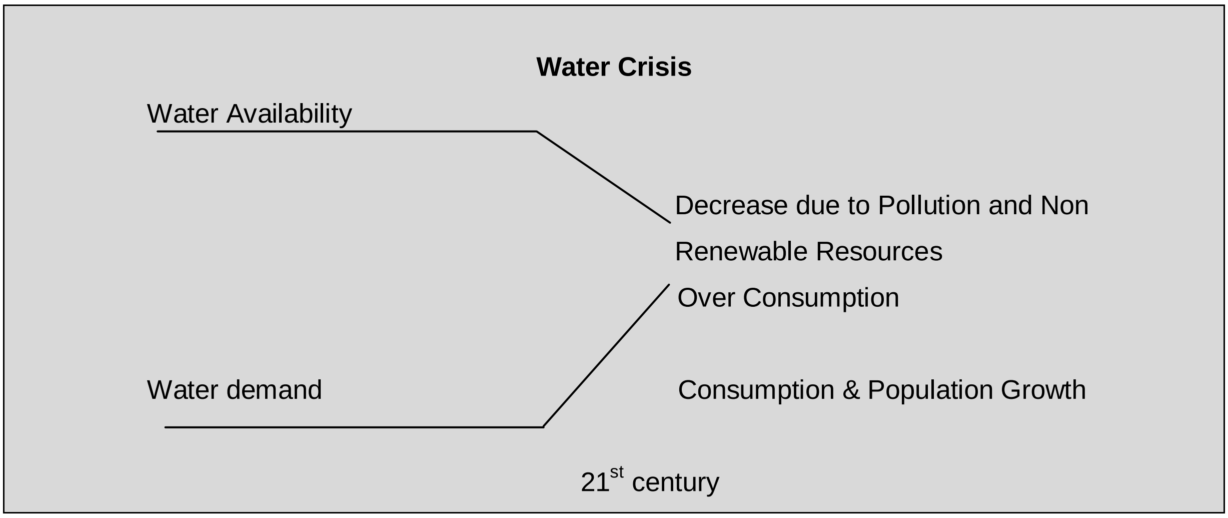


Figure A1.9 Future Water Crisis

Water markets emerging all over the world are subject to several challenges such as:

- the lack of information of buyers and sellers;
- the effectiveness of governmental agencies responsible for approval the transactions;
- the effectiveness of regional water agencies in defining politics for transfer and costs;
- the problems connected to the utilisation of salvaged or conserved water;
- the introduction of public interest and public trust doctrine in administrative and judicial decision making.

Appendix 2 Iceberg Environment

A2.1 Flora in Antarctica

Despite the severe life conditions, there is a considerable diversity in Antarctic flora. Vegetation can not develop extensively because of the harsh climate (Wasley, 2004). A combination of difficult conditions, such as freezing temperatures, poor soil quality, lack of moisture or lack of sunlight, inhibit the development and flourishing of plants (Everson, 1977). The AAD (2008[1] n.p) reported that there are:

> [T]hree main factors which determine the distribution of plant life in Antarctica.
>
> - climatic factors (frequency/duration of freeze/thaw cycling, temperature, free water)
> - edaphic factors (substrate characteristics, soil type underlying geology)
> - biotic factors (effects from other animals and plants) …
>
> To survive here plants need to be able to withstand severe physiological stresses, such as repeated freezing and thawing, desiccation and changes of the environment.

Consequently, the floral composition of Antarctica is dominated by non-vascular plants consisting of some 200 species of lichens, 100 mosses, around 50 species of bryophytes, and several hundred species of algae (mostly as phytoplankton) (Drew, 1977[2]). According to the BAS (2007 n.p.): "[T]here are two species of flowering vascular plants found in the Antarctic Peninsula: Antarctic hair grass *(Deschampsia Antarctica)* and Antarctic pearlwort (*Colobanthus quitensis)*" growing in summer only for a few weeks (Figure A2.1a and Figure A2.1b, Figure A2.2a and Figure A2.2b).

[1] http://www.antarctica.gov.au/about-antarctica/fact-files/plants
[2] http://herbarium.msu.edu/SSP/Introduction-M.html

Figure A2.1a and b Antarctic Hair Grass[3] Antarctic Pearlworth[4] (credit Universite Joseph Fourier, 2006; Rossum, 2001 n.p.)

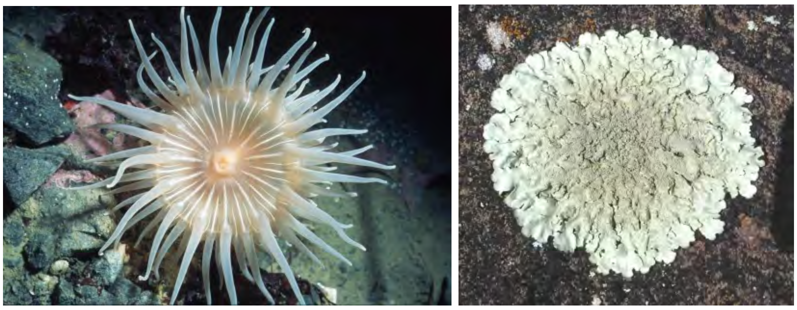


Figure A2.2a and b Antarctic Underwater Life[5] Lichen Squamulose[6] (credit BAS, 2008; Guinther, 2003 n.p.)

The availability of free water and the aridity are determinant factors for plant distribution in Antarctica (Everson, 1977). In contrast to the impoverished littoral flora and fauna, sub littoral communities are diverse and complex. Algae are confined to areas of exposed shoreline and regions of the shallow sub littoral with a rocky substrate (Drew, 1977). The duration and the severity of ice abrasion influence algae growth as well as do location and topography of the site, incident light levels, water clarity and wave action (Richardson, 1979). The limit of the photic zone is variable depending on the effects of the ice cover. Some plants have been collected at depths up to 700 m in the Ross Sea (Zaneveld, 1966, 1968, 1969) but light levels at this depth are insufficient for autotrophic production so specimens were probably carried by ice or currents (Drew, 1977). A large number and variety of invertebrates live in association with algae, which provides shelter and a source of food.

A2.2 Fauna in Antarctica

Due to the extreme cold at these latitudes land fauna is dominated by invertebrates (Andriashev, 1965). Sea ice is a major component of the Antarctic ecosystem. According to Sullivan *et al*. (1988), during winter sea ice provides a habitat for algae that bloom in spring

[3] http://www.humanflowerproject.com/index.php/weblog/comments/flowers_of_antarctica_all_two_of_them/
[4] www.rossum.com/antarc01/antarc6/images/flower.jpg, www.rossum.com/antarc01/antarc6/antarc6.htm
[5] http://ecology.com/ecology-today/2008/12/03/antarctic-icebergs-affecting-marine-life-as-deep-as-500-meters/
[6] http://commons.wikimedia.org/wiki/File:Lichen_squamulose.jpg

and summer, being a food source for permanent living species in Antarctica shrimps, krill urchins, and krill (Hagen *et al.* 1996; Kock, 2000). In turn, krill, an abundant prey resource, particularly during the austral summer, underpin the survival of many larger animals such as mammals (whales, seals), fish, cephalopods (squid) and birds (albatrosses and petrels) (Ainley *et al*., 2003, Figure A2.3).

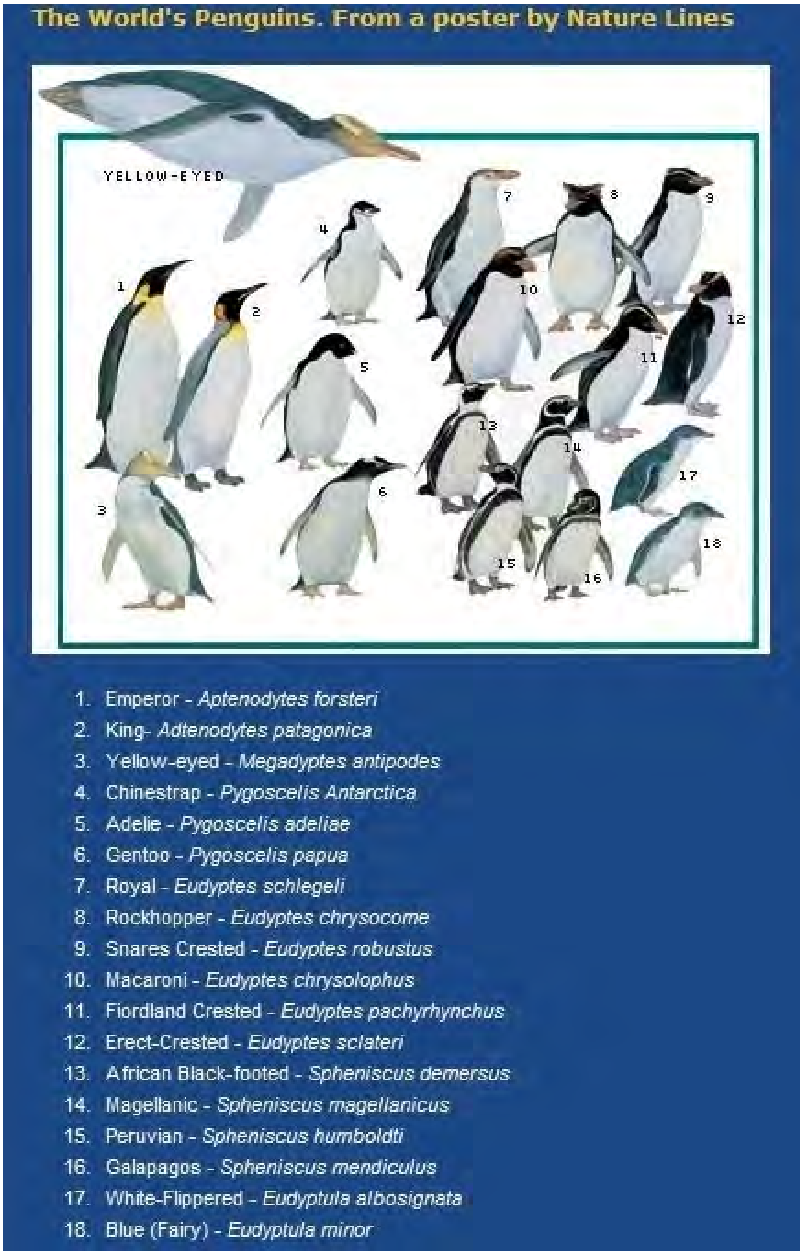


Figure A2.3 The World's Penguins (credit Nature Lines, 2004[7] n.p.)

[7] http://yellow-eyedpenguin.org.nz/penguins/other-penguin-species/

Mysids, amphipods and polychaetes are important as prey for coastal Antarctic fishes (Arntz and Clarke, 2002). Antarctic coastal fish communities are unique in the world, and are the result of millions of years of coadaptation and coevolution of the original fauna. The significance of sedentary fish species (*Nototheniidae* = Antarctic cods, *Bathidraconidae* = Dragon fish, *Channichthyidea* = Ice fish, *Harpagiferidae* = Plunder fish) in the ecosystem is of primary importance in Antarctica (Figures A2.4a, b ,c,).

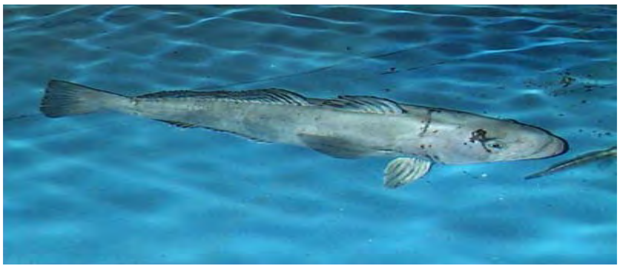


Figure A2.4a Antarctic Cod (credit Gutt[8] 2007 n.p.)

Figure A2.4b Antarctic Ice Fish (credit Gutt[9] 2007 n.p.)

Figure A2.4c Dragon Fish (credit Gutt[10] n.p.)

[8] http://tea.armadaproject.org/Images/atwood/atwood_mawsoni6.jpg
[9] http://scienceblogs.com/mixingmemory/upload/2007/02/icefish.bmp
[10] http://fascinatingly.com/wp-content/uploads/2008/06/fang-tooth-marine.jpg, http://www.awi.de/fileadmin/user_upload/News/Selected_Topics/Biodiversity/Life_below_Ice_Shelves/Photos_for_Download/20070124_Eisfisch_JGutt.jpg

Figure A2.4d. Plunder Fish (credit Gutt[11] 2007 n.p.)

The majority of notothenioid fish species (95%) are endemic to the Antarctic Region, and only 70% of the non-notothenioid fishes are endemic (Eastman and Eakin, 2000). Northern fish species (Plaice, Halibut, Mackerel icefish, Lanternfish, Eaton's fish, Patagonian toothfish) and crabs, invertebrates, isopods, copepods, molluscs (in ice) are not permanent inhabitants in Antarctica but migrate there (Schnack-Schiel *et al.*, 2004[12]; Koch and Frolkina, 2005; Frolkina, 2005a and b and Figure A2.5).

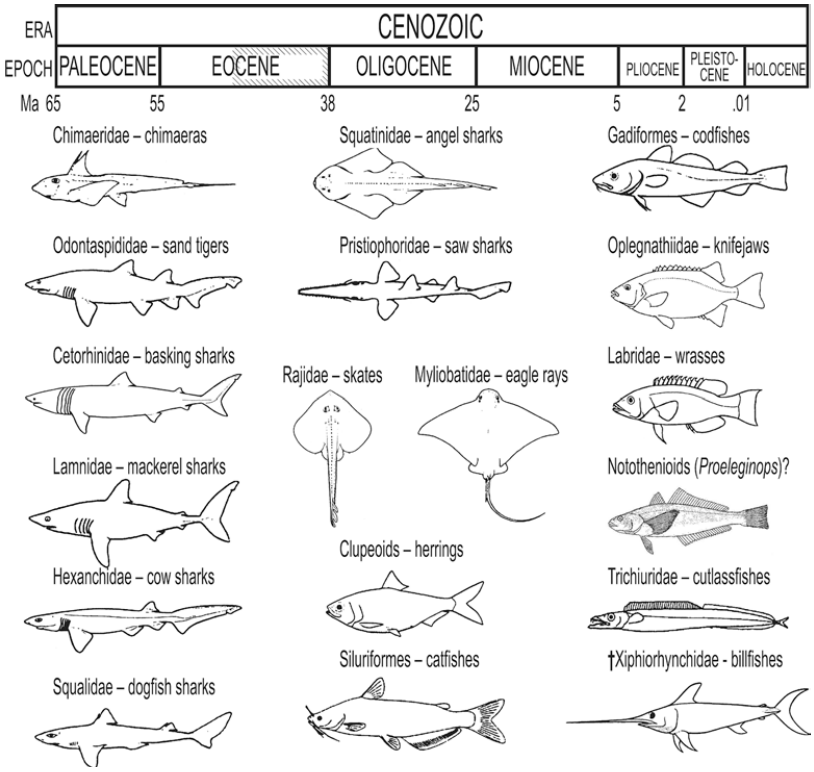


Figure A2.5 The Nature of the Diversity of Antarctic Fishes (credit Eastman, 2004[13] n.p.)

[11] http://www.solcomhouse.com/images/bernacchii.jpg
[12] http://www.sos.bangor.ac.uk/staff/pdf/DT_Schiel_2008.pdf
[13] Additional information and discussion is in Eastman (2000). The Xiphiorhynchid is a recent addition to the fauna (Cione et al. 2002) and the dagger indicates that this family is extinct. Outline drawings

Approximately 65% of coastal fish species are located in Antarctic high latitudes with a 'circum Antarctic', a 'lesser Antarctic' or a 'greater Antarctic' distribution range (Kock, 1987). Seasonally, the ice cover is linked to intense biological activity in Polar Regions (Ferreyra *et al.*, 2004). The phytoplankton distribution corresponds to fish species distributions. According to Targett (1981, p. 243): "[L]ow fish species diversity precludes the necessity for fine division of food resources within vertical habitat zone".

According to Ferreyra *et al.* (2004[14] p.1): "[E]very year, ice melting induces the stabilisation of the water column which can be observed until 150 km from the margin of seasonal ice, favouring the development of profuse phytoplankton blooms". The vertical distribution of fish species can be described using three groups (Andriashev, 1975 and 1976):

- stenobathic species inhabit near shore waters to -100 m depth;
- eurybathic species inhabit the entire continental shelf to -3,200 m;
- pelagic species occupy the continental slope and deep sea basins down to -5,475 m.

Fish play a local role in the diet of the Antarctic fauna. The principal fish predators are squids, whales, seals and sea birds (such as albatrosses, shags and petrels (Hureau, 1994). The annual fish consumption in the Southern Ocean by mammals and birds is estimated to be about 15 million t (Everson, 1977; Lau, 1985). Attempts to exploit Antarctic fish stocks commercially date back to the beginning of the last century.

The limits of the Antarctic benthic region are difficult to define because the Southern Ocean merges with the Atlantic, Pacific and Indian Oceans, although the Antarctic continental shelf is generally narrow, varying in width from 64 to 240 km and areas of the ocean floor obviously come under an Antarctic influence (Arntz and Clarke, 2002).

About 60% of the Antarctic biomass is in the form of large sessile organisms (Krell *et al.*, 2005). Estimates of biomass (Krell *et al.*, 2005) reflect the characteristic features of the Antarctic benthos. Shallow sub littoral regions with well developed macro algae have higher epifaunal biomasses than severely ice affected coasts (Park *et al.*, 1999). In sheltered bays, up to 30 m deep, soft substrates of muddy sand are generally characterised by a high

from Nelson (2994), Smith and Heemstra (2986) and Norman (2937) show modern representatives of fossil groups http://www.feriaantarticaescolar.cl/doc/disponibles_inach/23%20Eastman-The%20nature%20diversity%20Antarctic%20fishes.pdf

[14] http://vertigo.revues.org/3172

density and diversity of feeding polychaetes, molluscs and crustaceans (Park *et al*., 1999). Deeper benthic regions with hard substrates have a high biomass, which is generally greater than that of other comparable areas of the world's oceans. The abundance of hard substrates on the sea floor increases the areas available for attachment and hence increases the dominance of large sessile organisms such as sponges and holothurians.

Changes in the extent of sea ice would have consequential impacts on the ecosystems of Antarctica (Garrison *et al*., 1986). Deeper benthic regions have communities, determined largely by the nature of the substrate and attached fauna resembles the fauna found in deeper parts of the world's oceans (Andriashev, 1975; De Witt, 1971).

Sea temperatures below 30 m in the Antarctic Ocean and the abyssal zones of the world's oceans are very similar. The type of benthic sediments is a more important factor than temperature in determining the composition and distribution of Antarctic benthic organisms (Hagen *et al*., 1996). Since most of the ferruginous deposits come from ice as it floats north and melts, the northern limit of pack ice may therefore be the most valid limit of the benthos (Hagen *et al*., 1996). Within this area there are several unique physical oceanographic and ecological characteristics. The life cycles of key species in the ecosystem, such as krill (*Euphausia superba)*, strongly depend on ice dynamics (Hagen *et al*., 1996). This species is the main link between phytoplankton and higher trophic levels in the food web (mammals, fish, and birds) (Frolkina, 2005a and 2005b).

Field observations reported by Atkinson *et al*. (2004) revealed a replacement of krill by salps (*Salpa thompsoni*). Research conducted by Atkinson *et al*. (2004) in the South West Atlantic demonstrated that summer krill densities correlate positively with the extent of sea-ice from the previous winter. Krill need the summer phytoplankton blooms of South West Atlantic. According to Atkinson (2004), in South West Atlantic, winters extensive sea ice means plentiful:

> [w]inter food from ice algae, promoting larval recruitment and replenishing the stock. Salps, by contrast, occupy the extensive lower-productivity regions of the Southern Ocean and tolerate warmer water than krill … As krill densities decreased last century, salps appear to have increased in the southern part of their range. These changes have had profound effects within the Southern Ocean food web.

These changes could have consequences for both the biodiversity and the functioning of the Antarctic ecosystem, since salps represent a low energy source for high predators. Summer food and the extent of winter sea ice are thus key factors in the high krill densities observed in the South West Atlantic Ocean.

Measurement of the amount of plant pigment, such as the chlorophyll in a given volume of water, is used to estimate the phytoplankton standing crop (biomass per unit area or volume) and to study phytoplankton distribution and abundance. Large phytoplankton standing crops are found in the Scotia Sea, in the Bransfield and Gerlache Straits, the waters adjacent to the Antarctic Peninsula in the southern Ross Sea and in the south-western Weddell Sea (Smith and Nelson, 1986; Vernet *et al.*, 2009[15]). Another extensive bloom of the diatom is encountered in the south-western Weddell Sea (El Sayed, 1971; El-Sayed and Fryxell, 1993). It is estimated that the area affected by that bloom is at least 15,500 km^2 in extent. Coastal waters off the Antarctic continent and off the sub Antarctic Islands are, in general, characterised by higher standing crops of phytoplankton than open oceanic regions. Higher values are reported in the margins of the Antarctic and sub Antarctic islands than in adjacent areas. Except for isolated pockets of dense phytoplankton biomass, only small phytoplankton standing crops are found in the Drake Passage in the Bellingshausen Sea and in the open oceanic regions of the Antarctic seas. The vertical distribution of chlorophyll shows maximum values at depths to which 25 to 50% of surface light intensity penetrates. Below this, there is a progressive diminution in phytoplankton biomass to the depth of the photic zone (about 100 m), with little beyond this point (Vernet *et al.*, 2009[16]). In the Antarctic practically all photosynthetic production is compressed into the 120 to 150 day austral light regime rather than spread throughout the year as occurs at lower latitudes. Krell *et al*. (2005) studied phytoplankton dynamics in the eastern Weddell Sea from autumn to winter, during the transition period which marks the onset of sea ice formation. Changes in sea ice extent and ice movements would have impact on the availability of free water (amount and distribution). New distribution of fresh water affects the type and number of marine organisms found on the seabed. This fact may cause changes in the distributions of key species in Antarctica (Dayton *et al*., 1969).

[15]http://polarphytoplankton.ucsd.edu/docs/publications/papers/Vernet_MS_%20Icebergs_Subm042710.pdf
[16]http://polarphytoplankton.ucsd.edu/docs/publications/papers/Vernet_MS_%20Icebergs_Subm042710.pdf

Appendix 3 Impacts of Iceberg Transportation

A3.1 Iceberg Production and Melting Figures

Figures on ice accumulation and loss in the Antarctic from Hult and Ostrandor (1973) are given.

Table A-1

ICE ACCUMULATION AND LOSS IN THE ANTARCTIC

Loss Mode to Sea	Catchment: Area ($\times 10^{10}$ m^2)	Catchment: Mass ($\times 10^{15}$ kg/yr)	Discharge: Melt ($\times 10^{15}$ kg/yr)	Discharge: Icebergs ($\times 10^{15}$ kg/yr)
Ross Ice Shelf (54×10^{10} m^2)	232	0.33	0.23[a]	0.10
Ronne-Filchner Ice Shelves (48×10^{10} m^2)	292	0.45	0.33[b]	0.12
All other ice shelves (56×10^{10} m^2) }	873.5 (all other ice shelves, direct glacier streams and ice sheet combined)	1.62 (combined)	0.44[c]	0.74
Direct glacier streams }			0.10	0.22
Ice sheet }			0.10	0.02
Total	1397.5	2.40	1.20	1.20

[a]Average melt rate, back of throat = 0.36 m/yr.

[b]Average melt rate, back of throat = 0.5 m/yr (tidal extremes twice the magnitude and twice the frequency of those at Ross).

[c]Average melt rate over bottom = 0.9 m/yr.

The estimated losses from the iceberg discharge and melt that are consistent with an approximate balance between accumulation and loss and the known data in the Antarctic are given in Table A-1. The estimated losses from the deep ice shelves (Ross, Ronne-Filchner) are predominantly from melt ($\sim$0.7), while those from the shallow ice shelves and direct glacier streams are principally from icebergs ($\sim$0.6). The total Antarctic losses are estimated to be nearly equally divided between melt and icebergs. Of course, all the loss is eventually in the form of melt, but for the purposes of Table A-1, the melt loss indicates only the melt from attached ice flow and does not include the melt from detached icebergs even if they are locked in fast ice.

Figure A3.1 Ice Accumulation and Loss in the Antarctic Hult and Ostrander (1973[1] p. 28, 29)

A3.2 Iceberg Production Impacts

In this appendix, figures on ice accumulation and loss in the Antarctic from Hult and Ostrander (1973) are given.

ations. Although the *sea* ice is generally less than 2 m thick (compared with a few hundred meters for most tabular, fresh water icebergs), the area of sea ice formed and thawed each year is thousands of times the total area of icebergs and about ten times the mass. Thus sea ice is a major factor to contend with in the acquisition of icebergs. Its moderating influence on the climate (together with that of the continental icecap) is so dominating over that of the icebergs that little climatic effect would be expected, even with the complete removal of the total annual iceberg yield. It

Figure A3.2 Iceberg Transportation Climatic Impact Hult and Ostrander (1973[2] p. 31)

[1] http://www.rand.org/pubs/reports/2008/R1255.pdf
[2] http://www.rand.org/pubs/reports/2008/R1255.pdf

Appendix 4 Water Transportation Technologies

A4.1 Icebergs Shape Characterisation

McKenna's approach for three dimensional iceberg shape characterisation satisfies hydrostatic considerations, and ties the above and below water portions in a consistent manner (PERD/Report 20-77, 2004; and McKenna, 2005). The modelling procedure based on probabilistic simulations, represents measured relationships between waterline length, waterline width, height, draft and mass. The primary index dimensions used to represent iceberg shape and size are:

- waterline index *L*, the maximum water plane dimension;
- waterline width *W*, the maximum water dimension in the direction perpendicular to water line length;
- height *H* the maximum elevation of the iceberg above the water surface;
- draft *D* the maximum depth of iceberg keel.

Using these data, coefficients for icebergs characterisation called block coefficients can be calculated. The block coefficients are computed for icebergs' volume above and under the waterline, using the following equations:

a) the block coefficient for the above water volume (*Va*), equation A4.1

$$f^{a}_{VLWH} = \frac{Va}{LWH} \qquad \text{eq. A4.1}$$

b) the block coefficient for the under water volume (*Vu*), equation A4.2

$$f^{u}_{VLWH} = \frac{Vu}{LWH} \qquad \text{eq. A4.2}$$

The block coefficients have been derived theoretically from various characteristic shapes (wedge, pyramid, dome, tabular and dry-dock). Another important physical parameter of an iceberg is the overall centre of mass, which is the distance between the centre of mass and the mean iceberg surface (Figure A4.1).

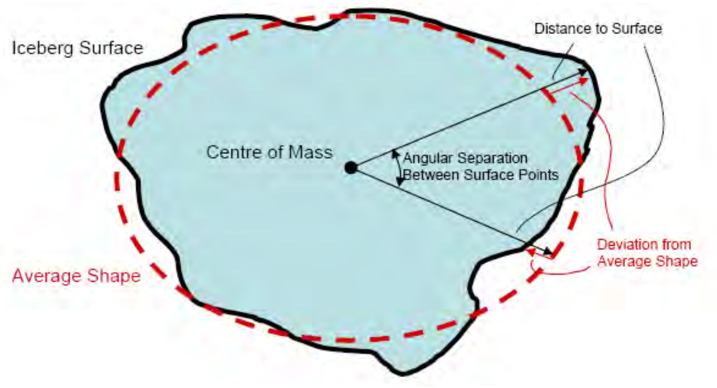


Figure A4.1. Representation of an Iceberg Centre of Mass (credit PERD/Report 20-77 2004 n.p.)

From physical point of view, there is a relationship between the maximum height of an iceberg and the above centre of mass. The overall centre of mass can be calculated when underwater contours only are available with the equation A4.3:

$$Z = \frac{(Z_a V_a + Z_u V_u)}{V} \qquad \text{eq. A4.3}$$

where:

Z is the distance to the centre of mass, with the indices *a* or *u* corresponding respectively to above and under water.

V is the overall iceberg volume.

Va and *Vu* are the volumes above and underwater.

The overall volume is estimated with the equation A4.4:

$$V = (\frac{\rho_w}{\rho_i})V_u \qquad \text{eq.A4.4}$$

where ρ_w is the density of water (1,025 kg/m^3) and ρ_i is the density of ice (900 kg/m^3).

The above water volume is estimated with the equation A4.5:

$$V_a = (\frac{\rho_w}{\rho_i} - 1)V_u \qquad \text{eq.A4.5}$$

For modelling it is necessary to consider two more parameters (Table A4.1):

- the ratio of above water centre of mass to above water height, such as: $f_{ZH} = \frac{Z_a}{H}$

- the ratio of above water centre of mass times waterline area to the above water volume,

such as: $f_{ZAV} = \frac{Z_a A}{V_a}$, where *A* is the waterline area.

Figure A4.2 shows the 4D schematic radial representation of a theoretical generated modelled iceberg. The waterline separates the above and underwater volumes. The draft is calculated to be 0.9 times the waterline length on average. The height is found to be 1/8 of the waterline length and 1/7 of the draft, both of which are in agreement with the experimental measurements.

Table A4.1 Above Water Shape Parameters (credit PERD 20-77 2004 n.p.)

Shape	**Factor of peak**	**Volume & area factor** $f_{ZAV} = \frac{Z_a A}{V_a}$	**Height factor** $f_{ZD} = \frac{Z_a}{H}$
Semi ellipsoidal	-	¾	4/8
Cone or pyramid	-	¾	¼
Cylinder or cube	-	½	½
Truncated wedge	0 (pyramid)	¾	¼
	1/2	Not calculated	0.4
Truncated cone or pyramid	0	¾	¼
	1/2	Not calculated	0.49
	1 (tabular)	½	½

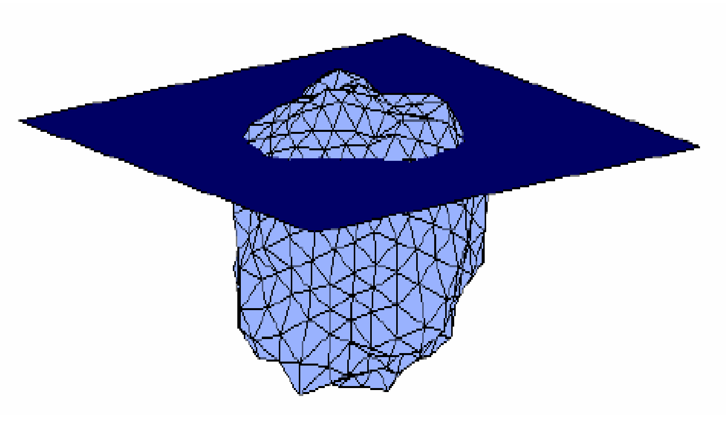


Figure A4.2 4D Radial Representation of a Modelled Iceberg (credit PERD/Report 20-77 2004 n.p.)

A4.2 Mass Estimation Process

The estimation of icebergs' mass is based on empirical relationships. Work undertaken by Smith and Donaldson (1987) is shown in Table A4.1. Their measurements were conducted between 1984 and 1985 over locations covering the Strait of Belle Isle, the southern Labrador and the Grand Banks, Canada. The measurements were taken from a ship which followed the iceberg at a distance of 1 to 2 km and in the same time from of an aircraft. The waterline length of the iceberg, which is the largest horizontal distance across the iceberg at the water line, is measured from the aircraft. This parameter is relatively easier to observe than other geometrical characteristics of an iceberg.

In the case of iceberg transportation for water supply, precise estimation of the mass of an iceberg is necessary for:

- operational iceberg forecasting models;
- improving the accuracy of estimating water and air drag forces on iceberg which in turn improve the forecasting of iceberg drift;
- calculating the towing force required for icebergs' transportation;
- calculating towline length and number of vessels to achieve requires bollard pull;
- improving the towing catenary toolbox by estimating the mechanical properties of the tow cable and tow hawser (wire) by reducing the slippage and roll of icebergs;
- forecasting the sizes of the waterbags for icebergs liquid freshwater production and transportation;
- forecasting the land network for freshwater distribution;

For icebergs' mass calculation different empirical equations have been proposed because since today no theoretical method is developed for this purpose (Table A4.2).

The equation proposed by Barker *et al.*, (2004) on which the mass value is expressed as a function of waterline length and ice density, have a physical meaning, which is realistic and is very much different from the empirical one. The equations proposed by Freeman (2004) are dimensionally correct and digital images can be used to estimate the primary dimensions L, W and H. The first equation needs to assign the shape factor, f = 0.15 to 0.50. The second improved equation uses digital images to estimate L, W and H and calculate the appropriate shape factors based on the projected area in image and on the calibration procedure of profiled iceberg.

Table A4.2 Empirical Equations for Mass Estimation, M the mass L the waterlength

Equations	**References**	**Comments**
$M = 1.04\ L^{2.A4.17}$	Canates, 1999	Eq.dimensionally incorrect
$M = \ = 2.25\ L^{2.58}$	Canatec, 1999	Eq.dimensionally incorrect
$M = 0.97\ L^{2.78}$	Singh *et al.*, 1998	Eq.dimensionally incorrect
$M = 0.81\ L^{42.77}$	Fuglem *et al.*, 1995	Eq.dimensionally incorrect
$M = 0.44\ L^{2.9}$	Barker *et al.*, 2004	Eq.dimensionally incorrect
$M = 0.5\ \rho_{ice}\ L^4\cdot$ Where $\rho_{ice} = 910$ kg/m^4	Barker *et al.*, 2004	Eq. dimensionally correct
M = A4.1.12 *f LWH*	Freeman, 2004	Eq. dimensionally correct; where *f* = 0.15 … 0.5
$M = 7.12q\sqrt{f_1 f_2 f_3}(LWH)$	Freeman, 2004	Eq. dimensionally correct and $f_1 = A_1(LW); f_2 = A_2(LH); f_3 = A_3(HW)$

Appendix 5 Iceberg Water Cost

A5.1 Water Consumption

In this section we present estimates of Quilty (2001) of water availability in the world and water consumption of Australian cities (Table A5.1, Table A5.2).

Table A5.1 World Water Availability (credit National Land and Water Resources Audit In 1985 and National Land and Water Resources Audit, Audit No. 33[1] in Quilty, 2001 n.p.)

Region	Annual Renewable (km^3)	Withdrawal (km^3)	% of Available	Year
Africa	3996	145	3.6	1995
Europe	6234	455	7.2	1995
North America	5309	512	9.6	1991
Central America	1057	96	9.1	1987
South America	9526	106	1.1	1995
Asia	13206	1633	12.3	1987
Oceania	1614	17	1.1	1995
(Australia)	343	19	5.5	2000
Antarctica	1250	0	0	2000
World	41022	3240	7.9	1987

Table A5.2 Australian cities' water usage in ML (credit National Land and Water Resources Audit In 1985 and National Land and Water Resources Audit, Audit No. 33 in Quilty 2001 n.p.)

City	Water Use 1983/84 *	Water Use 1996/97 *	% Change
Adelaide	182.8	214.65	17
Brisbane	144.9	183.9	27
Canberra	67.5	50.7	-25
Hobart	19.86	36.6	84
Melbourne	406.6	500	23
Perth	322	314.6	-3
Sydney	473	480.9	2

[1] http://www.nlwra.gov.au, http://www.freedrinkingwater.com/water_quality/quality1/13-08-icebergs-for-drinking-water.htm

A5.2 Iceberg Water Costs Estimates

Estimates of Rowden-Rich (1986 a and b p. 4 and p. 6) are presented in Figure A5.1:

- 5 -

4. STATISTICS.

Hypothetical nominal dimensions were assumed for estimating both capital and operating costs for the proposed commercial operation.

The size of the iceberg selected for operational plan studies was 500,000 m.t. This size is close to the observed maximum frequency percentile of 1,000,000 m.t. and furthermore, icebergs approximating this size may be dealt with by tugs of 5,000 SHP which are available and have been used in North Sea Oilfield operations.

Continental Shelf Depth	- 100 metres.
Point of Landing	- near Kangaroo Island, S.A.
Iceberg Size (nominal)	- 100 X 100 X 100 metres (with an irregular volume 56 percent of the cube).
Iceberg Draft	- approximately 86 percent of the vertical dimension.
Ice Specific Gravity	- .92
Iceberg Location	- 4000 km SW of Australia. - Latitude 55° S approximately. - Longitude 75° E approximately. (in the vicinity of the Kerguelen Islands).
Current Velocity	- 2/3 knot (0.33 m/s.)
Current Depth	- at least 1,000 metres.
Iceberg Displacement	- 500,000 metric tonnes approximately.
Polar Tug	- 5,000 SHP
Towing Velocity	- 1 metre/sec (2 knots).
Static Bollard Pull	- 55 tonnes
Statistical Distribution of Icebergs	- 1,000,000 metric tonnes has the greatest percentile distribution.

12. DISCOUNTED CASH FLOW.

	Gross Revenue ($)	Operating Costs ($)	Gross Income ($)	Interest ($)
Year 6	+50,000,000	-20,000,000	+30,000,000	-5,000,000
Year 7	+55,000,000	-22,500,000	+32,500,000	-5,000,000
Year 8	+60,000,000	-25,000,000	+35,000,000	-5,000,000
Year 9	+65,000,000	-27,500,000	+37,500,000	-5,000,000
Year 10	+70,000,000	-30,000,000	+40,000,000	-5,000,000
		Total	+175,000,000	-25,000,000

	Depreciation Allowance ($)	Nett Profit Before Tax($)	Taxation	Nett Income AfterTax($)
Year 6	5,000,000	20,000,000	-10,000,000	+15,000,000
Year 7	5,000,000	22,500,000	-11,250,000	+16,250,000
Year 8	5,000,000	25,000,000	-12,500,000	+17,500,000
Year 9	5,000,000	27,500,000	-13,750,000	+18,750,000
Year 10	5,000,000	30,000,000	-15,000,000	+20,000,000
		Total	-62,500,000	+87,500,000

Cash Flow Summary

	Cash Flow ($)	Discount Factor (20%)	Present Worth ($)
Year 1	-250,000	1.00	-250,000
Year 2	-1,250,000	0.83	-1,000,000
Year 3	-3,000,000	0.69	-2,075,000
Year 4	-18,500,000	0.58	-10,750,000
Year 5	-27,000,000	0.48	-13,000,000
		Total	-27,075,000
Year 6	+15,000,000	0.40	+6,000,000
Year 7	+16,250,000	0.33	+5,375,000
Year 8	+17,500,000	0.28	+4,900,000
Year 9	+18,750,000	0.23	+4,300,000
Year 10	+20,000,000	0.19	+3,800,000
		Total	+24,375,000
Year 11	+21,259,000	0.15	+3,125,000
		Total	+27,500,000

BALANCE PERIOD = 6 YEARS FROM COMMISSIONING

Figure A5.1 Iceberg Water Costs Estimates (credit Rowden-Rich 1986 a and b p.)

Appendix 6 Technical Evaluations of Preliminary Testing

Technical feasibility evaluations for laboratory and in situ experiments and guidelines for the smallest scale of preliminary testing are given in this section to test parameters and progressively assess the capacity of iceberg transportation systems. These evaluations and guidelines follow the recommendations of Weeks and Campbell (1973), Hult and Ostrander (1978), Mauviel (1980), Sobinger (1985), and Rowden-Rich (1986a, b). According to Weeks (1980 p. 5): “the best way to appraise [iceberg transportation] problems realistically would be to experiment with test tows on a model scale using several techniques”. However the system established in this thesis differ from previous transportation systems proposals. Detailed studies could be completed as future research.

A6.1 Project Proposal

Table A6.1 gives the systemic elements, the operation description and the corresponding timing for icebergs freshwater transportation from Antarctica to WA and/or other countries.

Table A6.1 Operation Description for Icebergs Water Transportation from the AAT to WA

	Operations	**Description**	**Timing**
1	Selection of an “ideal iceberg”	Detection and selection of a tabular iceberg, elliptical section, without cracks	Several days
2	Iceberg modelling	Iceberg’s physical properties (geometry of a variable volume, gravity centre and axis)	Several days
3	Permanent sensing of gravity centre of iceberg and possible cracking (Figure A6.1)	Security reasons for humans and equipment. Melting sensing	Permanent
4	Bag construction over iceberg	Auto supporting netting structure peripheral circulation: for humans, maintenance, materials, equipment, storage	Several days
5	Iceberg’s wrapping with a net	Protection against degradation, cracking, with a net which enhance iceberg’s stability	Several days
6	Iceberg wrapping with an iceberg bag	Insertion of metallic net and protective structure	Several days
7	Collar attachment to iceberg’s bag, on the floating line	Auto supporting structure Melted water storage, and iceberg stabiliser	Several days
8	Melting of iceberg and collection of freshwater in a collar	Collection of the melted water into the iceberg bag collar. Devices for melting acceleration	1 years
9	Empty waterbags connexion to the collar	Empty waterbags stored in special parking and transported	One day

		to the connexion stands	
10	External netting	Protection against mechanical destructive waves' action and system of attachment for transportation	One day
11	Bagged iceberg transportation	Transportation with currents and deflection with tug and kites	Several weeks
12	Fill-up of the waterbags	Fill-up the water bags with fresh melted water	24 hours for a waterbag
13	The links	Disconnecting of the water bags from the collar.	Two days
14	Train of waterbags	The train would be composed from 10 rows of three links.	One day
15	Kite attachment to the train		One day
16	Sustainable transportation of the train with the maritime currents	Deflection with kites and transportation with currents	Several weeks

Sustainable transportation system management of icebergs freshwater proposed in this project rests upon new concepts related to the transportation of the melted freshwater (the design of two different types of bag, one for the in-situ production of the iceberg water and a second one for iceberg transportation as the iceberg would melt in the bag, collected into a collar and then the water is transported in waterbags), using transportation bags, and the maritime currents and winds and kites. This system consists of the in-situ collection of the freshwater obtained from melted icebergs into a collar and of the transportation of this freshwater by a train of bags propelled by kites and maritime currents from Antarctica to WA. The elements determined for a sustainable iceberg transportation system in this thesis are detailed in Table A6.2.

Table A6.2 Elements of Sustainable Iceberg Transportation System

Elements for a 1 million m^3 iceberg	**Size for a 200 m by 100 m by 50 m**
Foam	600 m by 50 m by 1m = 3,000 m^3
Collar	600 m by 50 m by 30 m 900,000 m^3 expandable up to 600 m by 50m by 300 m 900,000m^3
Bag	9000,000 m^3 500 m by 180 m by 1m
Nets	9000,000 m^3
Waterbags	80 waterbags of 17,000 m^3 and 100 m by 16 m
Kites	50m by 10 m

As suggested by Hult (1978), in the modelling process the first step consists of undertaking preliminary research on the critical operating components of the transportation system. According to Hult and Ostrander (1973 p. VII), in their studies:

> “[b]efore designing and developing an operational system (...) a test program with icebergs would be desirable to determine the nature of the submerged surfaces of tabular icebergs; test techniques for insulating and harnessing icebergs; measure the transport environment and performance; determine how well the Coriolis forces can be controlled; and test the performance of modelling to simulate operational control and performance”.

Table A6.3 describes different experiments necessary for the proposed technology for icebergs freshwater transportation, laboratory experiments and field experiments.

Table A6.3 Proposed Laboratory Tests and Field Experiments

Operation	**Laboratory tests**	**Field experiments**
Wrapping the iceberg with a uniform belt, an internal net and a megabag	Simulation, experiments	Real scale
Assembling the collar, the external net and the mega bag	Simulation, experiments	Real scale
Iceberg behaviour during melting	Simulation, experiments	Real scale
Collar behaviour during water transferring process	Simulation, experiments	Real scale
Bag behaviour during water transfer, connection into the train, and transportation	Simulation, experiments	Real scale
Kites behaviour during train navigation	Simulation, experiments	Real scale
Bags behaviour at destination	Simulation, experiments	Real scale
Bags reutilisation	Experiments	Real scale
Materials Testing for: Nets, Megabag, Collar, Waterbags, Kites	Experiments	Real scale

Melting and transporting viabilities have continuously been throughout previous projects major preoccupations and key aspects of the previous studies Weeks and Campbell (1973), Hult and Ostrander (1973), Mauviel (1980), Sobinger (1985), and Rowden-Rich (1986). Mauviel (1980) studied towing and wind propulsions on iceberg models simplifying variable dimensions issues. According to him (Mauviel, 1980, p 5.[1]): “corrections were made to the windspeed gradient linked to the height above the water surface”, and “linked to the alteration of the incident wind angle due to flow around the model”. It is therefore possible to extrapolate the intervening parameters with a Froude similitude (velocity / (length x gravity)) even if critical Reynolds numbers ((velocity x width) / viscosity) were not reached for the air and water flows.

[1] http://www.igsoc.org/annals.old/1/igs_annals_vol01_year1980_pg123-127.pdf

In this thesis, the hydrodynamic stability reliability of melting iceberg and the feasibility of an iceberg water transportation system from Antarctica to WA represented major uncertainties with relatively no available scientific data. It was identified in previous projects as mass loss, floating stability and transportation propulsion issues Weeks and Campbell (1973), Hult (1978), Mauviel (1980), Sobinger (1985), and Rowden-Rich (1987). Critical operating components to enhance the stability of the iceberg and of the iceberg water transportation were extracted and selected from previous projects and new available technologies to design a new system of operation. This proposed system consisted of a bagged iceberg melting and transporting system and a waterbag oceanic transportation system. These components would require preliminary laboratory experiment.

A6.2 Preliminary Laboratory Experiments Evaluations

The preliminary experiments would consist of undertaking testing on scale models with corresponding physical characteristics of the materials (Murphy, 1979). The elements, principles and conditions of the associated experiments are explained in Table A6.4.

Table A6.4 Iceberg Operating Experiments Elements, Scales, Principles and Conditions

Elements	**Real scale model in m**			**1/1,000,000 scale model in m**			**Principles**	**Conditions**
Size	Length	Width	Depth	Length	Width	Depth	Experiments under different conditions of wind and currents speeds and temperatures, salinity	Test basin
Iceberg model	200	100	50	2	1	0.5		
Iceberg foam net protection bag model	600	50	1	6	0.5	0.01		
Collar	600	50	30	6	0.5	0.3		
Megabag	500	180	1	5	2	0.01		
80 waterbags	100	15		1	0.15			
Kites	50 m /10 m 5,000 kW. power			0.1 to 4 m/s towing simulation				
Currents power	Currents power 3 m/s							

Guidelines for the two critical operating components which would require preliminary laboratory experiment will be proposed now. The first experiment concerns the decay, melting and the deterioration of a bagged ice block and its stability in the bag in a pool at different temperatures and salinity levels. The objective is to establish the stability of the collar-belted bagged and netted iceberg in waves. The selected iceberg would be belted uniformly with a first protective sheet of cylindrical elements which could be passed around the iceberg. A net structure, a mega-bag envelope and a collecting collar and then an external surround the iceberg. The collar is made out of waterbags. The collar by its floating surface and as the density of the melted iceberg water, lower than the sea water's, could be used as a melted freshwater storage and stabilise the iceberg's equilibrium during melting.

A6.3 First Experiment: Melting Iceberg Hydrodynamic Stability

The behaviour of the sack during the collecting process of the water and in wind and waves would be studied. The experiments would help to calculate the level of reinforcement required to ensure that the progressive melting of the iceberg does not result in breaking the bag, and to optimize the collar bag net system properties. Several parameters have to be determined and elements to be modelled: scales of the foam, the net, the collar, the bag, the external net. According to Murphy (1978), icebergs modelling is based on severable variables:

> "[f]orce, control length, velocity, ice density, fluid density, fluid viscosity, acceleration of gravity, mass loss, specific heat, thermal conductivity, heat of fusion, ice temperature, time, intensity of solar radiation, angle of solar radiation, and absorption of solar radiation".

For a 1:2,000 scale a 2 km long, 0.9 km wide and 0.75 km deep iceberg would correspond to 1 m length by 0.45 m with and 0.38 m depth 150 kg ice block iceberg model. According to Bowring *et al.* (2010 n.p.[2]), "it is a manageable laboratory size". The iceberg model could be harnessed and its forces could be monitored in a water tank at specific velocities and directions, water and air temperatures corresponding to the location of iceberg operating (Bose, personal communication 2008). Proposed overhead lamps of proper intensity to simulate solar radiation and stated that a 200 transportation period would correspond to 4 and a half days of simulation (Bowring *et al.,* 2010). In our experiment a model of 4 m length by 1 m width and 0.5 m depth of 2 t of ice for a scale of 1:2,500 would represent a real scale tabular iceberg of 10 km length, 2.5 km width and a 1.25 km depth 10 km^3 iceberg. Actually, the model weight should be close to 1,800 kg as the freshwater density of tabular iceberg is close to 900 kg/m^3, as mentioned in Chapter 3 or reported by Hult and Ostrander (1973), Sobinger (1985) and Eik *et al.* (2010). Iceberg properties would be monitored (stability, drag,

[2] http://web.mit.edu/12.000/www/m2012/finalwebsite/solution/glaciers.shtml

buoyancy). The temperature of the iceberg ocean, the currents, the winds as well as the climatic conditions need to be identified, measured, reproduced and simplified. These parameters depend on icebergs origins and locations. With these parameters, iceberg characteristics such as its shape, volume, inner temperature and physical composition can be determined and compared. The modelling characteristics would be obtained from them (Mauviel, 1980[3]). The specific climatic conditions of the geographic catching zone of iceberg and drifting areas could be simulated. Information regarding iceberg drift tracks, the waves of the float line, bottom topography, decay rhythms north of 60° S, freshwater flow, currents, temperature, salinity, and significant wave heights would be combined to support the experiments and the simulation of iceberg harvesting.

The weight (which is about the weight of the amount of ice melted), the buoyancy (the freshwater is floating), the drag, the static forces and the hydrodynamic ones (waves), the temperature, the stiffness effects would be predetermined from technical estimations and compared with experiment (Loset, 1993).

A6.3.1 Modelling Guidelines of the Characteristics of the Iceberg

Tabular icebergs are more stable than small icebergs. Regarding stability issues, the above water shape of the iceberg is critical (Figure A6.1).

Figure A6.1 Tabular Iceberg in Antarctica (credit: NOOA[4], 2005 n.p.)

[3] http://www.igsoc.org/annals.old/1/igs_annals_vol01_year1980_pg123-127.pdf
[4] http://commons.wikimedia.org/wiki/File:Tafeleisberg.jpg?uselang=de , http://web.mit.edu/12.000/www/m2012/finalwebsite/solution/glaciers.shtml

The transportation system described in this thesis is based on large tabular icebergs operating. To model them, the process consists of reproducing with a block of ice these physical characteristics of the iceberg. Physical modelling, with a large ice block in a test tank, would be used to simulate iceberg behaviour during melting over a range of conditions (Mauviel, 1980). There are several kinds of ice, dry ice (which melts quickly) flake ice which breaks more and crystal block ice which is denser but needs lower temperatures and more freezing time (Figure A6.2).

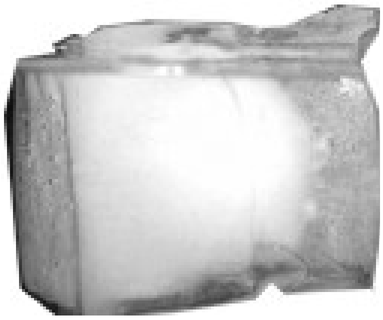


Figure A6.2 Experimental Ice Cube n.d. n.p.

Standard icebergs of 1 m^3 could be produced from freshwater. To produce the ice sample, the ice would be frozen in a special container. A plastic drums or a 2.5 t bin chip could be used (Bose, personal communication 2008). It is possible to obtain different types of shapes (Bush, personal communication 2007). For example for the sake of simplicity the ice blocks could be of cylindrical shape and circular section of 70 cm diameter and 40 cm height. However the ice blocks should be designed as close as possible to the shape of the iceberg (which is an important parameter on which depends the melt). In this view a bin has to be put two weeks in a freezer. Nowadays the ice is produced in cutting fridges (before it was in power fridges). There are several companies able to produce ice samples. The commercial price is around AU$200/t (Bush, personal communication 2007).

A6.3.2 Collar, Bag and Net System Model Materials

Two types of bags would be studied in this experiment, the collar for melted water collection, and the megabag for iceberg wrapping and transportation. The bags would be produced from the same material as the bags commercially available and currently used for freshwater transportation. For the bag properties information, measurements and assessments could be provided by the companies which already producing waterbags. For the iceberg internal net and the iceberg megabag, specific designs were proposed in the thesis, on the model of a purse or a concertina with a holding net inside and pleats (rings) down the bottom (Wakeford, personal communication 2008). The type of material used for the bag model could be a sample of bags if it is possible to obtain some. Another option for the model would be to use a canvass sand sail maker like for dodger boats (Bose, personal communication 2008). The bagging materials of ice companies could also be used. Basic thermal 10 kg bags of 1.2 m by 0.6 m by 1.2 m are a potential option, suitable to study iceberg stability, in the conditions of the suggested experiment (Bush, personal communication 2008). For the closure a zipper system could be used such as for Spragg bags (Spragg, 2001). First the material would be tested, then, a bag model could be produced by integrating the parameters of iceberg bags to the model and its material characteristics, to iceberg properties, such as its resistance, the foil properties, the strength, the frictions, the elasticity of the fabrics, as well as the effects of temperature, waves, safety (Chemical Hazards Response Information System CHRIS, 2003). Studies on the heating features of the iceberg megabag would be required to match with the features of the real scale bag. The bag would be placed in position and would stay inside the collar.

To model the collar in which the melt water of the iceberg model would be transferred, the size should be adapted to the scale of the experiments. The coupling collar attached to the bag would be modelled with a plastic elastic bag or with a flexible elliptic pipe.

The drag of the collar would depend on its shape and characteristics, but it is reasonably possible to assume that the collar could be modelled with a depth $1/4^{th}$ of the iceberg's and an expansion capacity of 4 times the width of the iceberg. As the in-situ real scale collar would have appropriate semi rigid reinforcement at its edges, the experimental stage collar would need to have corresponding properties strength and resistance, capacities. To transfer the water from the bag to the waterbag collar, buckle pipe section drainage tubes, roughly with 20 mm large high density polyethylene, rod or wire could be used (flexible aluminium, or plastic welding rod) (Wakeford, personal communication 2008). An external transporting net would be added around the bag respecting the scales.

A6.3.3 Science Involved in Melting Iceberg Stability Modelling

The results from laboratory experiments could be used to design numerical models of iceberg melting which could include fluid mechanics studies on ice fracture physics (Chapter 2). This would enable testing of the stability mechanism during the transfer of melted water into the collar, which occurs throughout melting processes. A 3D simulation could be conducted to later validate the experiments.

Undertaking experiments at the Australian Maritime College (Launceston, Tasmania) on the stability of water melting and transporting system of bagged iceberg had actually been considered during my PhD. The AMC has a Fume Tank facility where these experiments could have been conducted. In the see-through flume tank (5 m long, 4 m large, 2 m deep), it would be possible to model slow movements of the iceberg encapsulated into a bag, using a visual system for the measurement of stability, waves dynamics, currents and wind effects. The methodology principles are still presented in the next section. These experimental methods correspond to the same types of principles of experiments than several other tests including melting tests carried out by Daley (Veitch and Daley, 2001, p.39):

> Blocks of ice, representing icebergs, were used to study how icebergs melt and what factors affect the melting. The blocks were tested in three different conditions, and tests were performed. All tests were conducted in a small tank, with a depth of 34 cm and water temperature of from 15°C to 16°C. The air temperature was about 17.5°C. Two different block sizes were used. The first was a cube, (0.248 m x 0.248 m x 0.254 m), and the second was a slab (0.273 m x 0.197 m x 0.152 m).

The cubes had volumes around 15.6 cm^3 and the slab had volumes around 8.17 cm^3. The cube weight was around 14 kg and the slab around 7.3 kg. The three different conditions included calm water, small waves (of 1 to 2 mm and 3 Hz) water, calm water with a strong solar insulation (100 W lamps).

Rectangular blocks roll at 45° whereas cubic blocks roll at 90°. Veitch and Daley[5] reported that rolls was not very well predictable. However they demonstrated that rolling occurred earlier and more often in waves conditions (Figures A6.3a, b and c)

[5] ftp://ftp2.chc.nrc.ca/CRTreports/PERD/Iceberg_evol_00.pdf

Figure A6.3a Iceblock Cube Rolling (credit Veitch and Daley, 2001 A9)

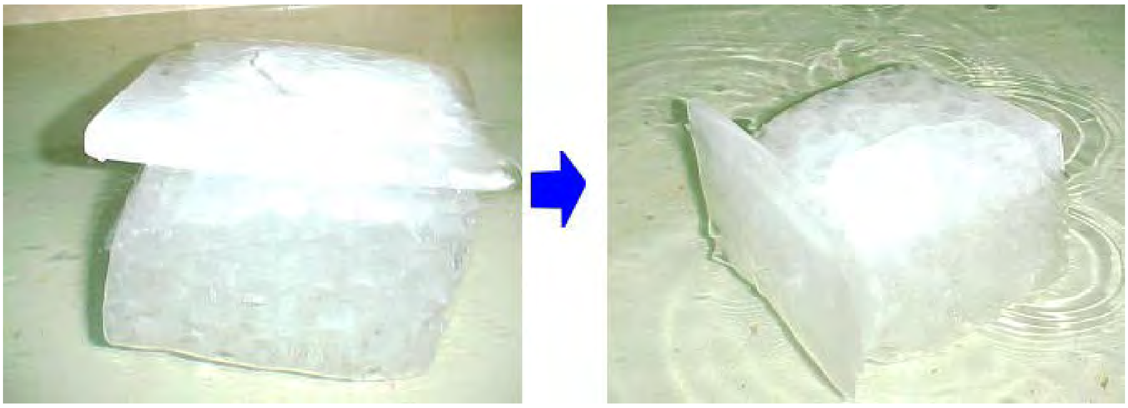


Figure A6.3b Iceblock Cube Rolling (credit Veitch and Daley, 2001 A9)

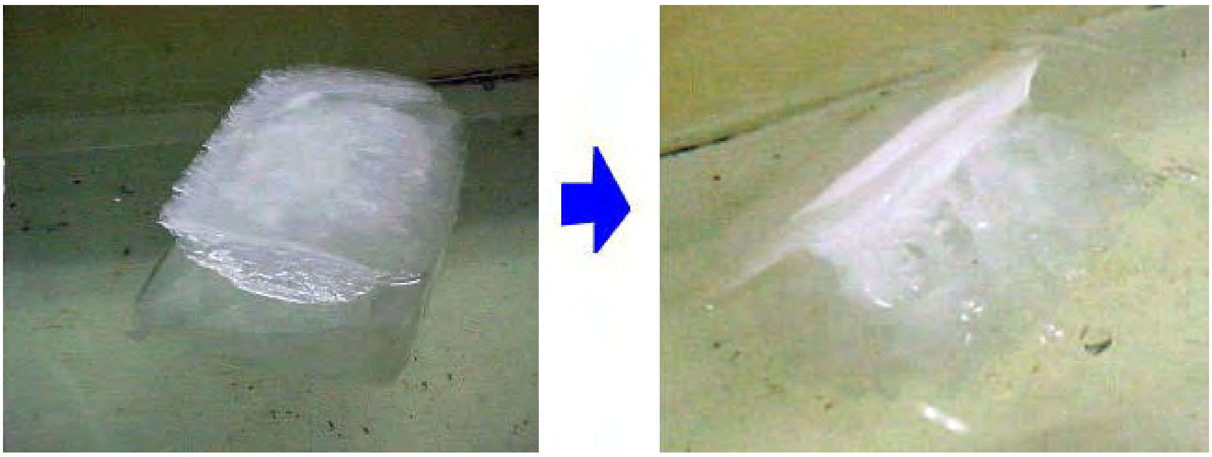


Figure A4.3c Rectangular Iceblock Rolling (credit Veitch and Daley, 2001 A9)

White et. al. (1980), reported that several types of melting can occur, depending on the melting patterns of the blocks. In Veitch and Daley the analysed melting patterns included 4 sides and the bottom and the top of the ice block melting, 4 sides melting or 4 sides and the bottom of the ice block melting (Figures A6.4a, b and c).

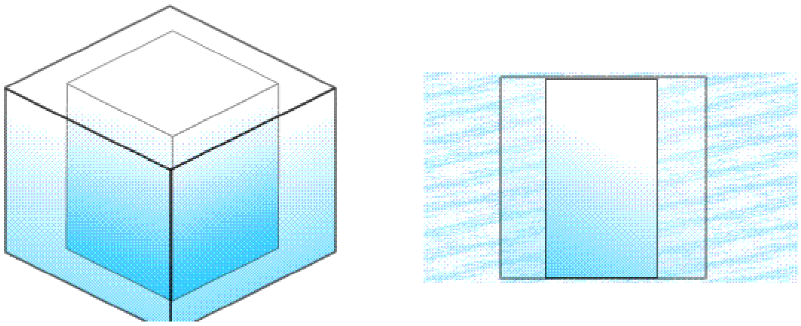


Figure A6.4a Four Sides Melting (credit Veitch and Daley, 2001 A10)

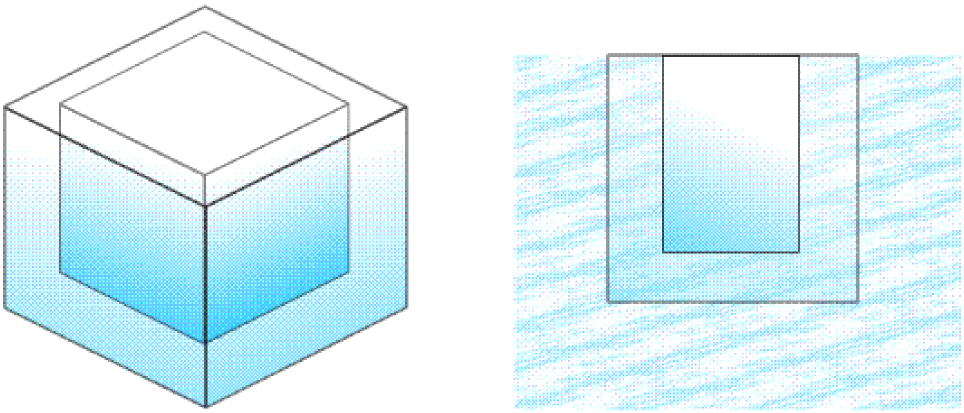


Figure A6.4b Four sides and the Bottom and the Top of the Ice Block Melting (credit Veitch and Daley, 2001 A11)

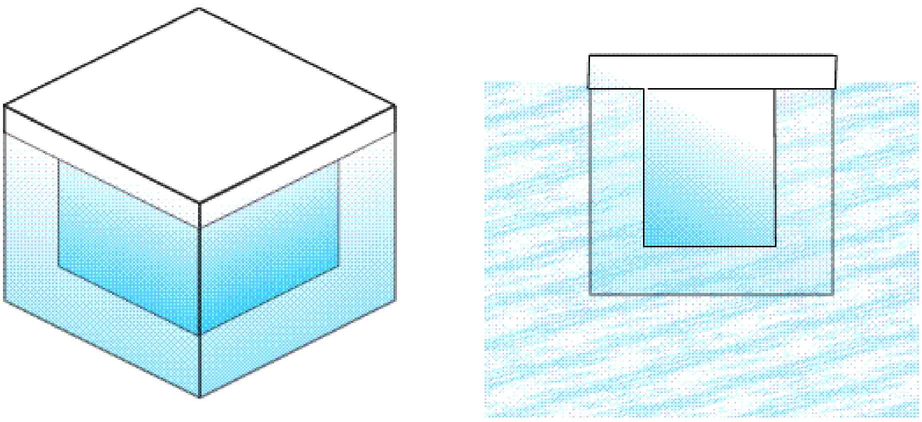


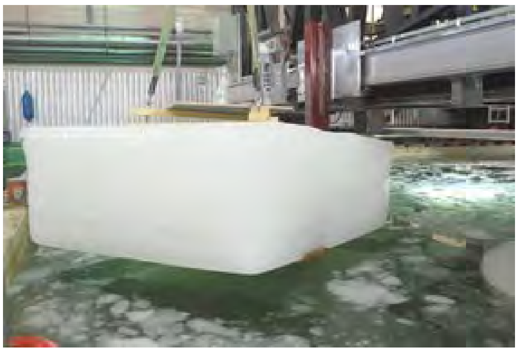
Figure A6.4c Four sides and the Bottom of the Ice Block Melting (credit Veitch and Daley, 2001 A12)

A6.3.4 The Bagged Iceberg Stability Testing Methodology

The ice block would be frozen with spikes in it to be able to later handle it and then removed from the container. For the transport, a truck and a lifting device (cranes) would be needed to lift and displace the 1t container. Therefore attachment links would be put in it in order to be able to use the chains after or a trailer to transport it and to use the measurement tools before the ice is created. In terms of modelling, the 1:40 scale iceberg towing tests experience of Eik *et al.* (2010[6]) undertaken in the HSVA ice tank can provide guidelines as it was used to model smaller scales icebergs deflection techniques. Two different iceberg models were created in wooden frames (rectangular and cylindrical) filled with freshwater ice pellets, and put in an ice tank for several days (Figures A6.5a and c).

Figures A6.5a Ice Block Removed from Freezing Frame (credit Eik *et al.*, 2010 n.p.)

When the ice was frozen into solid blocks, the wooden forms were removed (Figures A6.b).



Figures A6.5b Ice Block put in Water (credit Eik *et al.*, 2010 n.p.)

[6] http://www.hydralab.eu/project_summary_report.asp?id=52

Figures A6.5c Iceblock in the Modelling tank (credit Eik *et al.*, 2010 n.p.)

In the experience proposed in this section the protective belt, the net system, the bag, the collar and in its containers would be placed on the sides of the ice sample. The sheet would be tightened on the top of the iceberg model. This sheet would let the melt water passing directly in the bag. The melt water would be transferred in the collar.

The bagged ice block would be melting in the water. The sensors would be installed. The temperature and the salinity would be controlled adding ice flakes and salt. For the salinity of the water, as the basin is filled with freshwater, the differential would be integrated to calculations to take in account the salinity factor.

Melt rhythms and the deterioration of the ice block in a dynamic environment would be studied undertaking temperature measurements at precise times. As the time of the experiment does not correspond to the time of melt, a correlation would be assessed (the currents, the temperature and the wind effect), with solar radiation simulated by heat lamps.
To measure the deterioration of the iceberg in the bag, special tools would be used. The melt could be measured with acoustic transducers (krautkramer types) or floating corner camera. The ultrasonic velocity in water is about 1,450 m/s at 20°C and about 3,000 m/s in ice. The scale effects estimations for the sensors would be assessed. The process of calibration would happen before. Tests would be undertaken every hour to take in account non linear rates of ice melt. In Eik *et al.* (2010) tests, a QualiSysTM motion system was used to record iceberg motions. Subsequently, the experiments measuring the properties of the model could start. To simulate the drift speed a slow towing force could be applied. In the experiment of Eik *et al.* (2010), iceberg models have been towed in four different ice concentrations. 2 m^3 models of 80,000 t icebergs were used for a 1:40 scale. At another scale, for example at 1:400, these models would correspond to a small 1 million t iceberg

which is a size close to the economically viable size of iceberg operating with non fossil fuel energies defined in this thesis (Chapter 10). In Eik *et al.* (2010) experiment, tow line forces, iceberg displacements and rotations were recorded. A 4 mm Liros Dyneema TM rope and a 3 mm steel cable were used to simulate the towing. It corresponded to a 16 cm diameter rope and a 12 cm diameter steel hawser at full scale (Eik *et al.,* 2010). Towing simulation was completed by attaching load cells at the tank carriage and at each of the two tow line branches. Based on these ratios, in the experiment proposed in this section 1mm high strength cables would correspond to 1m steel cable which corresponds to the expected size to harness and transport a 10 million t iceberg (Sobinger, 1985).

Stability, drag, buoyancy, the strength, and the elasticity of the wrapping and collecting structures would be measured. The bagged iceberg subsurface profiles could be acquired with ground penetrating radar. These measurements would provide a continuous time series of water transfer into the collar. The forces effects and the stiffness (response) of the materials, the metacentric height, and the Gm, the weight, the buoyancy, the drag, the static forces, the hydrodynamic ones (waves), the motion would be measured.

For the ice properties, the forces, the motion, and the waves effects, inclination tests would be undertaken. The goal of the stability test is to measure the resistance of the bags. The inclining tests consist of moving weights on the tested element and then to make some angle calculations. The angle and force of the moving weights as well as the response of the ice blocks would be monitored. A systematic method would be determined: A visual system in (flume tank) would be used, with stereo vision which would allow quantitative measurements of the movements to measure the stability on the icebergs. For the measures, strain gages for sensor connections would be inserted. The process of calibration would happen before.

Monitoring of encapsulated iceberg when transported to warmer waters allows to measure the impacts of environmental and sea temperature on the melting and the transfer of fresh water into the collar and then in waterbags.

A6.4 Second Experiment: Iceberg Water Waterbags Transportation

The second experiment would concern iceberg water transportation system from Antarctica to WA. Iceberg transportation systems would be by their nature highly power-consuming activities. The transportation system studied in this thesis aimed to reduce the fossil-fuel energy consumption by optimising the use of the natural energies that could be obtained from currents and winds. The bags would drift on ¾ of the trip. Giant 100 to 200 m kites would pull a line at 100 m to give direction and control to the train (Breukels and Ockels, 2007). Based on the experiments undertaken by waterbag companies (Spragg, Medusa, Aquarius, NWS), a technical study on waterbag properties could be completed in order to create a model. These experiments would be based on the simulation of the main currents of the designated route from the original operating location to the delivery site in WA. Experiments to assess the forces required to launch and deflect large icebergs and their water in specific waterbag transportation systems using the currents as the main driving forces could be undertaken. According to (Murphy, 1978) it is possible to obtain practical information from small-scale models of iceberg transportation and to adequately model power, requirements, marine architectural designs, optimal velocities and sailing conditions.

A6.4.1 Waterbag Modelling Principles

The goal of the towing stability test would be to improve the iceberg water transportation system. The aim is therefore to measure the stability of a waterbag and a waterbag train models transported with natural energies. Testing the bags and the train resistance would allow to avoid their breakage, and to improve their assembling techniques. Assessing the parameters of this experience would be based on information about iceberg tracks north of 60° S as well as tides, current, wind, sea state and sea ice extent.

The towing and the natural drift simulation would be done through the towing system of a towing tank. The propulsion system, the acting forces of the natural energy, the currents forces, the winds and their effects on the transportation system (drifting tools and kites) would be modelled with a slow towing line and a wave simulator.

A6.4.2 Making the Waterbag Models

The first part of the experiment would concern a model of the waterbag. Using the details from the bag companies special ocean transportation waterbag design would be adapted following the conclusion of a naval architecture hydrodynamic study with specifications be as close as possible to the reality of what could be an current drifting and kite towing iceberg water transportation bag (Barras, 2004) . The properties of the new bags naval design (shapes, the zip systems, the ballasts, the pressurization systems, the lateral reinforcements, hull, stern, bow, top, keel, valve system, and catamaran filets specifications), such as the distribution of the propulsion force and the water and air pressures inside the sack, the connectors forces could be determined from existing waterbags (Spragg, 2001). The model would consist of a bag with modelled naval accessories: the bag fabric could be made out of an inflatable polyethylene plastic bag, and the accessories could be an attaching system and flippers and derives respecting the materials and resistance specifications of the real scale ones.

The second part of the experiment would concern a model of the train of waterbag (Chapter 7). Transporting the iceberg water in waterbag trains would have significant hydrodynamic and advantages in terms of maritime transportation (Hult and Ostrander, 1973; Sobinger, 1985). Several layers of foam, fibre glass plastic or polystyrene close cell could be filled with water and used to create a model of a train. The modelled naval accessories could be a spider web system of connection between the bags.

The resistance of the modelled would need to be adapted to the scale of the experiment. However for a 1:2,500 scale iceberg waterbag train of 1 million t capacity. Bags dimension would be 100 m by 17.5 m diameter and a train would contain three rows of 20 bags so would be around 2 km length which correspond to a 0.8 m long train of 20 bags of 40 cm length and 7 cm diameter. The bags would be filled with water. Stability test under a simulated towing and current would be undertaken to assess the resistance of the bags. The towing rope used to simulate the currents and winds forces could be a 1 mm towing rope (corresponding to a 1m high strength towing rope). A virtual transportation condition is proposed. Based on the experiments undertaken by kites companies (Skysails, Kiteship), a study on kites in order to define the properties of new types of kites necessary for the waterbag control could simplify and pre suppose the hydrodynamic aspects of the aerofoil kites and their drag and lift possibilities (Naaijen, Koster and Dallinga 2006). The natural drifting speed is around 2 km/h and 8 km/h with the currents and kites specific propulsion tools (0.5 and 2 m/s).

The Australian Maritime College (AMC, Launceston, Tasmania) has a Test basin and a Fume Tank where these experiments could be conducted (Figure A6.6a).

Figure A6.6a Modelling Facilities AMC n.d. n.p.

The Test basin (AMC, 2010[7]) allows to have a difference of wave's responses, and to choose waves: it is a long tank and can provide a uniform movement of 1.5 m/s (Figure A6.6b and c).

Figure A6.6b Test Basin Experiments, AMC n.d. n.p.

Figure A6.6c Test Basin n.d. n.p[8].

[7] http://www.amc.edu.au/maritime-engineering/model-test-basin

In the flume tank (AMC, Pollution[9]) (5 m long, 4 m large, 2 m deep), it is possible to model slower movements of the iceberg encapsulated into a bag, using a visual system for the measurement of stability, waves dynamics, currents and wind effects (Figure A6.6d, e and f). With these models, stability tests could be undertaken under a simulated towing and current.

Figure A6.6d Ship Model AMC n.d. n.p.

Figure A6.6e Towing Tank AMC n.d. n.p.

Figure A6.6f Towing Tank AMC n.d. n.p.

[8] http://www.amc.edu.au/sites/default/files/Berthed%20Ship%20Motions_1.JPG
[9] http://www.amc.edu.au/maritime-engineering/towing-tank

A6.4.3 The Waterbag Stability Test Methodology

For both experiments ultrasonic floating sonar transducer (Krautkramer) could be used as infrared camera which would allow quantitative measurements of the displacements of the waterbag as a function of time, and dynamics of waves. The simulation of the behaviour of the sack in wind and waves would start. The stability of the waterbag system under towing would be measured by repeated inclining tests. The inclining tests consist of moving weights on the tested element and then make some angle calculations using sensors and inclinometers. The propagation time, the metacentric height, the Gm, and static/hydrodynamic forces effects would be monitored. The outcomes of these experiments are to improve the specific designs of freshwater transportation bags. 3D simulations could corroborate the results (Figure A6.7a and b).

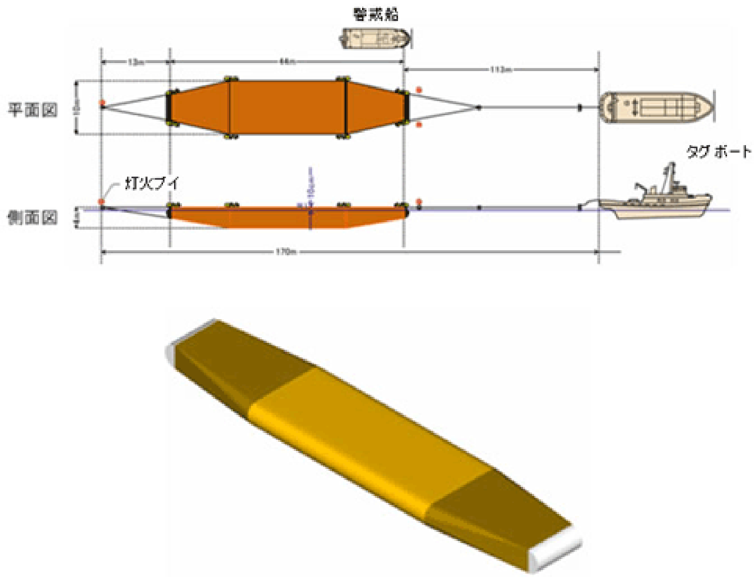


Figure A6.7a and b Waterbag Simulations (credit Monohakobi Institute 2008 n.p.)

In the first part of the experiment, the waterbag would be filled with water; the sensors would be set up and installed. The scale effects estimations for the sensors would be assessed. The process of calibration would happen before. The simulation of the behaviour of the waterbag in wind and waves would start. The stability of the waterbag under towing would then be measured by repeated inclining tests. In the second part of the experiment the train of waterbag connections would be set up. The sensors would be installed calibrated and the scale effects estimations for the sensors would be assessed as for the first part. The simulation of the behaviour of the train in wind and waves would start. The stability of the waterbag train system under towing would then be measured by repeated inclining tests.

A6.5 Logistic Support

The logistic support required for this project is composed of bags and ice operating materials, and kites information. Sensors materials, information and expertise would be necessary to test the decay and the stability of an encapsulated iceberg model and the behaviour and the drift, of a transported waterbag model or a transported freshwater waterbag train model. Because of the time-intensive nature of the work, logistic constraints for the experiments and the costs of the project, the logistic support should be ensured by consortium of research centres, polar agencies, and large commercial operators.

A6.6 In-Situ Experiments

Using the results of the laboratory experiments, new materials specific to an iceberg transportation system from the AAT to WA could be developed. The next stage would be to test them in-situ with a detailed logistic support, remote sensing tools, research ice breaker tugs or ships, helicopters, ROV, bags and iceberg operating materials, kites, funding and scientific collaboration. Figure A6.8a and b show full scale waterbag experiments.

Figure A6.8a and b Waterbags Experiments (credit Monohakobi Institute 2008 n.p.)

Sensors materials, information and expertise would be necessary to test the decay and the stability of an encapsulated iceberg and the behaviour and the drift, of a transported waterbag or a transported freshwater waterbag train. Prescriptions on the scales of these in situ experiments have been given (Chapter 7, Chapter 10).

A6.7 Conclusion

The propositions of experiments concerning iceberg transportation systems would allow to further assess the technical feasibility of the melting system of iceberg and to evaluate the conditions and assumptions described in this thesis: the reliability of the melting times and the reliability of the stability of the melting icebergs and the reliability of the drifting and the kite transportation system. These points are crucial to investigate in order to secure an efficient sustainable system of iceberg transportation based on the use of non fossil energies.

GLOSSARY Acronyms and Abbreviations

3D Three Dimensions

AAD Australian Antarctic Division

AAS Australian Academy of Science

AAT Australian Antarctic Territory

AATSR Advanced Along Track Scanning Radiometer

ACC Australian Climate Control

ACE Antarctic Climate and Ecosystems

ACI Australian Climate Institute

ADCP Acoustic Doppler Current Profiler

ADRO Adaptive Dynamic Range Optimization

AFP Agence France Presse

AGNWC

AIS Amery Ice Shelf

ALFS Airborne Low Frequency Sonar

ALOS Advanced Land Observation Satellite

AMAP Arctic Monitoring and Assessment Program

AMC Australian Maritime College

AMISOR Amery Ice Shelf Ocean Research

APF Antarctic Polar Front

ARC Australian Research Council

ARMCANZ Agriculture and Resource Management Council of Australia and New Zealand

ASAC Antarctic Science Advisory Committee

ASOC Antarctic and Southern Coalition

ASPIRE Antarctic Science and policy: Interdisciplinary Research Education

ASTER Satellite Imagery and Satellite System Specifications

ASW Amorphous Solid Water

ATA Antarctic Treaty Area

ATBA Areas to be avoided

ATCM Antarctic Treaty Consultative Meeting

ATCP Antarctic Treaty Consultative Parties

ATEP Australia's Antarctic Treaty Environmental Protection

ATME Antarctic Treaty Meeting of Experts

ATP Antarctic Treaty Party

ATS Antarctic Treaty System

ATSR Along Track Scanning Radiometer

AUV Autonomous Underwater Vehicles

AVHRR Advanced Very High Resolution Radiometer

BAS British Antarctic Survey

BMBF Bundesministerium für Bildung und Forschung

BPI British Polar Institute

BPRC British Powerboat Racing Club

CASI Compact Airborne Spectrographic Imager

CBA Cost-benefit Analysis

CCAMLR Commission for the Conservation of Antarctic Marine Living Resources

C-CORE Centre for Cold Resources Engineering

CEE Comprehensive Environmental Evaluation

CEP Convention of the Committee for Environmental Protection

CGMS Coordination Group for Meteorological Satellites World Meteorological Organization

CHC Canadian Hydraulics Centre

CIF Costs Insurance Freight

CIS Canadian Ice Services

CMA Calcium magnesium acetate

CMB Cosmic Microwave Background

CNRS Centre National de la Recherche Scientifique

CRAMRA Convention on the Regulation of Antarctic Mineral Resources

CRC Cooperative Research Centre

CRREL Cold Regions Research and Engineering Laboratory

CSA Cross Sectional Area

CSIRO Commonwealth Scientific and Research Organisation

DFG Germany - Deutsche Forschungsgemeinschaft

DHI German Hydrographic Institute

EEZ Exclusive Economic Zone

EMAS Eco-Management and Audit Scheme

EMP Environmental Management Plan

ENVISAT EnvIronment Satellite

EPA Environmental Protection Agency

EPBC Environment Protection and Biodiversity Conservation Act

ERS European Remote Sensing Satellite

ESA European Space Agency

ETH Eidgenössische Technische Hochschulen

EU European Union

EuphZ Euphotic Zone

FAO Food and Agriculture Organization

FLI Fluorescence Line Imager

GAS Geophysical Antarctic Survey

GEOSAT GEOdetic SATellite

GFDL Geophysical Fluid Dynamics Laboratory

GIS Geographic Information Systems

GNU GPL Gnu's Not Unix General Public License

GPS Global Positioning System

GRID Global Resource Information Database

HDA High Density

HGW Hyperquenched Glassy Water

HPPE High-Performance Polyethylene

HRS High Resolution Visual Scanners

ICESat Ice, Cloud, and land Elevation Satellite

IDA International Development Association

IEE Initial Environmental Evaluation

IFA Ingenieurburo fur Abfalltechnik

IFREMER Institut Francais de Recherche pour l'Exploitation de la Mer

IGY International Geophysical Year

IMO International Maritime Organisation

IPCC Intergovernmental Panel on Climate Change

ISO International Standard Office

IWHG Iceberg Water Harvesting Group

IWMI International Water Management Institute

LDA Low-Density

LEDC Less Economically Developed Countries

LIDAR LIght Detection And Ranging

LOSC Law of the Sea Convention

MAB Program Man and the Biosphere

MARPOL International Convention for the Prevention of Pollution From Ships

MBARI Monterey Bay Aquarium Research Institute

MCG Melbourne Cricket Ground

MEDC More Economically Developed Countries

MISR Multi-angle Imaging Spectro Radiometer

MIT Massachusetts Institute of Technology

MIZ Marginal Ice Zone

MMD Mining Machinery Developments Limited

MSL Mixed Surface Layer

MTS Marine Transportation System

MTSNAC United States Marine Transportation System National Advisory Council

N G National Geographic Magazine

NASA National Aeronautics and Space Administration

NCAR-CCM3National Centre for Atmospheric Research

NCEP National Centers for Environmental Prediction

NERC Natural Environment Research Council

NGA National Geospatial-Intelligence Agency

NGOs Non Governmental Organisations

NIC National Ice Centre

NLWR National Land Water Resources

NM nautical mile

NMEA National Marine Electronic Association

NOAA National Oceanic and Atmospheric Administration

NPV Net Present Value

NRC National Research Council

NRCC National Research Council Canada

NSF National Sanitation Foundation

NSIDC National Snow and Ice Data Center

NTIS National Technical Information Service US

NWC National Water Commission

NWI National Water Initiative

NWS Nordic Water Supply

NYK Nippon Yusen Kaisha

OECD Organisation for Economic Cooperation and Development

OTEC Ocean Thermal Energy Conversion

PACZ Polar Antarctic Cold Zone

PERD Panel on Energy Research and Development

PF Polar Front

PFZ Polar Frontal Zone

POC Particular Organic Carbone

POOZ Permanently Opened Ocean Zone

PROANTAR Programa Antártico Brasileiro

PVC Polyester Polypropylene

RADAR Radio Detection and Ranging

ROV Remote Operated Vehicle

SAF Sub-Antarctic Front

SAR Synthetic Aperture Radar

SAZ Subantarctic Zone

SCAR Scientific Committee on Antarctic Research

SCARM Standing Committee on Agriculture and Resource Management

SFSI Full Spectrum Imager

SIA Patrol The Sea International Authorities

SIWI Stockholm International Water Institute

SIZ Seasonal Ice Zone

SOLAS Safety Of Life At Sea

SPOT Satellite Pour l'Observation de la Terre

SST Sea Surface Temperature

STF Subtropical Convergence or Subtropical Front

TDS Total Dissolved Solids

UCAR University Corporation for Atmospheric Research

UK United Kingdom

UN United Nations

UNCLOS United Nations Convention on the Law of the Sea

UNEP United Nations Environment Program

UNESCAP United Nations Economic and Social Commission for Asia and Pacific

UNESCO United Nations Educational Scientific and Cultural Organization

USA United States of America

USGS United States Geological Survey

USIPS Under Sea Ice and Pelagic Systems

VHDA Very High Density Amorphous Ice

VNIR Visible Near Infrared

VTPI Victoria Transport Policy Institute

WA Western Australia

WAPC Planning Commission

WCD World Commission of Dams

WHO World Health Organization

WRC Water and Rivers Commission

WSAA Water Services Association of Australia

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