# Investigation of Meteorological Events Preserved in High Resolution Snow Pit and Firn Core Records

by

### **Alison McMorrow**

Bachelor of Arts (Geography) / Bachelor of Economics Bachelor of Antarctic Studies (Honours)

Submitted in fulfillment of the requirements for the Degree of

### **Doctor of Philosophy**

### University of Tasmania

June, 2006

## Declaration

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution. To the best of my knowledge and belief this thesis contains no material previously published or written by another person except where due acknowledgement is made in the text.

ALISON MCMCMORROW

# Authority of access

This thesis may be made available for loan and limited copying in accordance with the Copyright Act 1968.

ALISON MCMORROW

University of Tasmania June, 2006

# Acknowledgements

Many thanks are required here. First, I would like to thank my supervisors, Mark Curran, Tas van Ommen, Vin Morgan and Bill Budd. Thanks also to Rob Massom for taking over from Bill as a supervisor late in my candidature. A special thanks also to Anne Palmer for her incredible depth of chemistry knowledge and patience with my incredibly basic chemistry questions. Thanks also to the many faces of Glaciology, especially Barbara Smith for helping me dig and Linda van Ommen for conducting the hydrogen peroxide analysis that didn't quite make it into this thesis. Thanks also to Ian Allison for providing information on the AWS animal.

Big thanks to all the crew who transported me to Antarctica, up to Law Dome and helped dig all those pits, particularly Woll, Squizzy, Pete, Flea, Trev and Buzz! You guys provided many a laugh on those cold days and worked your butts off in the name of science (and a couple of glasses of red).

Thanks also to Ian Simmonds and his crew from the Uni of Melbourne for providing the back trajectory analysis, and to Neal Young from ACE CRC for providing the AVHRR images. Thanks also to the members of the ACE CRC, IASOS and the AAD for providing support and knowledge throughout my PhD. A fantastic bunch of people devoted to a special place.

I would also like to acknowledge the Antarctic CRC (now the ACE CRC) and the Trans-Antarctic Association for providing financial support for me to attend and present these results to the international scientific community.

A huge thanks goes to my family, my mum Brenda, my dad Jim, and my sisters Frances and Christine. You all helped me out over the years and I will never forget that. Also thanks to my friends, particularly Susan for her amazing desserts, Ruth for the horsey chats, Tash for her endless laughter and Grant for his beautiful music. A big woof-thanks to my puppies, Rama, Tilda and Zoe, who provided inspiration for snow pit names and many tail wags and nuzzles on the tough days.

Finally, to my fiancé Jimmy, and my son Liam. Your smiling faces provided the best encouragement and your cuddles the best comfort and support. Thank you.

# List of abbreviations

$\delta^{18}O$	oxygen isotope ratio
AAD	Australian Antarctic Division
ANARE	Australian National Antarctic Research Expeditions
AVHRR	advanced very high resolution radiometer
AWS	automatic weather station
CRC	Cooperative Research Centre
ENSO	El Nińo Southern Oscillation
DMS	dimethyl sulphide
DMSP	dimethyl sulphoniopropionate
DON	dissolved organic nitrogen
DoY	Day of Year
DSS	Dome Summit South
$H_2O_2$	hydrogen peroxide
HCL	hydrochloric acid
IC	ion chromatography
MSA	methane sulphonate
$N_2O$	nitric acid
NOAA	National Oceanic and Atmospheric Administration
nss SO <sub>4</sub>	non-sea salt sulphate
ОН	hydroxide
PSC	polar stratospheric cloud
SMOW	Standard Mean Ocean Water
$SO_2$	sulphur dioxide

## List of publications

<b>Type of Publication</b>	Number	Reference
Papers in refereed journals	6	1 - 6
Conference and seminar presentations	7	7 – 13

1. McMorrow, A. J., van Ommen, T. D., Morgan, V. and Curran, M. A. J. 2003. Ultra high seasonality of trace ion species and oxygen isotope ratios over 4 annual cycles. *Annals of Glaciology*. **39**. 34-40.

2. Curran, M., van Ommen, T., Palmer, A., Morgan V. and McMorrow, A. Non-sea-salt sulphate in ice cores, correction for sulphate depletion. (in preparation).

3. Pedro, J., Curran, M., van Ommen, T., Smith, B., Morgan, V., McMorrow, A. and Smith, A. High resolution snow pit study of 10Be at Law Dome, Antarctica. (in preparation).

4. McMorrow, A. J., Curran, M. A. J., van Ommen, T. D., Morgan, V. and Allison, I. 2002. Features of meteorological events preserved in a high resolution Law Dome snow pit. *Annals of Glaciology*. **35**. 463-470.

Curran, M. A. J., Palmer, A. S., van Ommen, T. D., Morgan, V., Phillips, K. L., McMorrow, A. J. and Mayewski,
P. 2002. Post-depositional methansulphonic acid movement on Law Dome and the effect of accumulation rate. *Annals of Glaciology*. 35. 333-339.

6. McMorrow, A. J., Curran, M. A. J., van Ommen, T. D., Morgan, V., Pook, M. J. and Allison, I. 2001. Intercomparison of firn core and meteorological data. *Antarctic Science*. **13**(3), 329-337.

Talk presented at the International Glaciological Society, International Symposium on Antarctic Glaciology.
Milan, Italy. 25<sup>th</sup> to 29<sup>th</sup> August 2003. Ultra high seasonality of trace ion species and oxygen isotope ratios over 4 annual cycles. McMorrow, A. J., van Ommen, T. D., Morgan, V. and Curran, M. A. J.

8. Talk presented in the Institute of Antarctic and Southern Ocean Studies seminar series. August 2003. Ultra high seasonality of trace ion species and oxygen isotope ratios over 4 annual cycles.

Talk presented by Andrew Smith at the 18<sup>th</sup> International Radiocarbon Conference. Wellington, New Zealand. 1<sup>st</sup> to 5<sup>th</sup> September 2003. Snow pit study of the deposition of cosmogenic beryllium at Law Dome, Antarctica. Smith, A. M., Pedro, J. B., Curran, M. and McMorrow, A. J.

Poster presented at the International Glaciological Society, International Symposium on Ice Cores and Climate.
Kangerlussuaq, Greenland. 19<sup>th</sup> to 23<sup>rd</sup> August 2001. Features of meteorological events preserved in a high resolution
Law Dome snow pit. McMorrow, A. J., Curran, M. A. J., van Ommen, T. D., Morgan, V. and Allison, I.

11. Talks given at Palaeoclimate Day at the Antarctic CRC (February 2002) and the Australian Ice Cores Conference at the Antarctic CRC (April 2002).

12. Talk presented by Andrew Smith at the 9<sup>th</sup> International Conference on Accelerator Mass Spectrometry, AMS – 9, Nayoga, Japan, September 9-13 2002. High resolution study of the deposition of cosmogenic 10Be and 7Be in Antarctic Snow. Smith, A. M., Curran, M., Pedro, J. B., McMorrow, A. J., Smith, B. T. and Morgan, V. I.

 Poster presented by Mark Curran at the 22nd General Assembly of the International Union of Geodesy and Geophysics. University of Birmingham, UK. 18-30th July 1999. McMorrow, A. J., Curran, M. A. J., van Ommen, T. D., Morgan, V., Pook, M. J. and Allison, I. 2001. Intercomparison of firn core and meteorological data.

## Abstract

A key problem in ice core palaeclimate studies is the interpretation of the various measurable parameters in ice in terms of climate and environmental conditions. This study is aimed at developing a closer understanding of the connection between high resolution snow/firn measurements and meteorological conditions. Ultra high resolution snow pit and shallow firn core records of oxygen isotope ratios ( $\delta^{18}$ O) and a suite of trace chemical species including marine biogenic sulphur compounds (methane sulphonate (MSA), non-sea salt sulphate), nitrate and major sea salt ions (sodium, chloride, magnesium), were generated at a high accumulation site on Law Dome, East Antarctica. Concordance between accumulation events identified in the records up to 7.7 km apart confirms that the observed chemical and isotopic variations are the result of regional rather than local surface effects. This allows calibration of the snow pit and firn core records with measured meteorological parameters.

Event scale dating of the records was established using hourly snow accumulation measurements from a co-located automatic weather station (AWS). The ultra high resolution nature of this study and independent dating scale provide an opportunity to examine exact timings in the seasonality of each chemical species. The traditional summermaximum species of  $\delta^{18}$ O and MSA show consistent relative phasing during mid-summer over four annual cycles. Nitrate shows an erratic seasonal cycle with a general trend characterised by narrow peaks during spring and early summer, preceding the mid-summer peaks in  $\delta^{18}$ O and MSA. Non-sea salt sulphate cycles indicate similar characteristics to MSA signals during summer, but are more comparable to nitrate signals during spring, autumn and winter. This suggests the summer non-sea salt sulphate signal is driven by biological activity, yet appears to be linked with nitrate signals outside the summer season. Finally, the sea salt species indicate a seasonal cycle characterised by maximum concentrations during autumn, winter and spring.

Event scale dating of the snow pit and firn core records allows direct comparisons between the chemical and isotopic signals and observed meteorological conditions. Local meteorological conditions recorded by the AWS are combined with synoptic scale meteorology derived from Advanced Very High Resolution Radiometer satellite imagery and back trajectory analysis to identify potential source regions and transport mechanisms influencing the chemical and isotopic signals. Potential source regions and transport mechanisms are examined for the marine biogenic indicators (MSA, non-sea salt sulphate). Results indicate that the seasonal variation in marine biogenic activity is reflected in the Law Dome records, and the sea ice zone provides an important source region. However, results also indicate that lower latitudes, and the Heard Island region (50°S, 70°E) in particular, may provide an important additional source region for MSA and non-sea salt sulphate outside the summer season. High sea salt signals are generally associated with intense cyclonic systems, yet variations in atmospheric circulation and transport mechanisms also impact on the sea salt record. Comparisons between  $\delta^{18}$ O signals and local air temperatures reveal the  $\delta^{18}$ O record is an excellent proxy for temperature at Law Dome, although high (warm)  $\delta^{18}$ O events are found to be influenced by atmospheric circulation and associated with rapid advection of air from low latitudes. Finally, results suggest that spring nitrate signals at Law Dome may be linked to the intrusion of stratospheric air through the breakdown in the polar vortex during spring.

# **Table of Contents**

Decl	aration .		ii
Ack	nowledge	ements	iii
List	of Abbre	eviations	v
Abst	t <b>ract</b>		vii
List	of Public	eations	v
Tab	le of Con	tents	viii
List	of Tables	s	xiv
List	of Figure	es	xiv
Cha	pter 1	Introduction and Review of Relevant Literature	1
1.1	Overvie	w	1
1.2	Oxygen	Isotopes in the Antarctic	2
	1.2.1	The Isotopic Composition of Precipitation	2
	1.2.2	The Ice Core Palaeothermometer	4
1.3	Trace Io	n Chemicals in the Antarctic	6
	1.3.1	Sea Salt Ions	6
		Sea Salt Particle Production	6
		Sea Salt Ions as Climate Indicators	7
	1.3.2	Marine Biogenic Sulphur Compounds	9
		The Natural Sulphur Cycle	9
		Marine Biogenic Compounds as Climate Indicators	. 10
	1.3.3	Nitrate	12
		Sources of Nitrate in Polar Snow	12
		Nitrate as a Climate Indicator	14
1.4	Depositi	on of Atmospheric Contaminants to Polar Snow	15
	1.4.1	Dry Deposition	15
	1.4.2	Wet Deposition	16
	1.4.3	Fog Deposition	17
	1.4.4	Drifting and Blowing Snow	18
	1.4.5	Post Depositional Modification of Chemical Species	19
1.5	Chapter	Summary and Thesis Outline	21

Cha	pter 2	Site Characteristics, Sample Retrieval, Preparation and Analysis	22
2.1	Overvie	w	22
2.2	Physical	and Climatological Conditions of Dome Summit South (DSS), Law Dome	22
2.3	Snow Pi	t Sample Retrieval	26
2.4	Firn Cor	re Retrieval and Sample Preparation	28
2.5	Sample	Analysis	31
	2.5.1	Oxygen Isotope Ratios ( $\delta^{18}$ O)	31
	2.5.2	Hydrogen Peroxide	31
	2.5.3	Trace Ion Chemical Species	32
		Methods	32
		Standards and Sample Calibration	34
2.6	Conclud	ing Remarks	37
Cha	pter 3	High Resolution Spatial and Temporal Comparison Across Law Dome	e 38
3.1	Overvie	w	38
3.2	Intra-Pit	Spatial Variability (30 cm to 2 m)	39
	3.2.1	The Rama Snow Pit	39
		Statistical Analysis of the Spatial Reproducibility	41
		Summary	45
3.3	Inter-Pit	Spatial Variability (50 m to 100 m)	46
	3.3.1	The Rama, Karioke and Paddy Snow Pits	46
3.4	Inter-Co	re Spatial Variability (100 m to 11.7 km)	48
3.5	Conclud	ing Remarks	60
Cha	pter 4	Local Meteorology at DSS, Law Dome	62
4.1	Overvie	w	62
4.2	Antarcti	c Meteorology	62
4.3	Automa	tic Weather Stations in the Antarctic and at Law Dome	63
4.4	Features	of Local Meteorology at DSS	65
	4.4.1	Air Temperature	65
	4.4.2	Wind Speed and Direction	70
	4.4.3	Atmospheric Pressure	76
4.5	Meteoro	logical Bias in Ice Core Records	81
	4.5.1	Snow Accumulation	81
	4.5.2	Local Meteorology of Accumulation Events at Law Dome	83

4.6	Conclue	ling Remarks	86
Cha	pter 5	High Resolution Dating of the Snow Pit Records	88
5.1	Overvie	W	88
5.2	Identific	cation of Net Accumulation Events	89
	5.2.1	Defining Events in the Rama and Matilda Snow Pits	90
	5.2.2	Accumulation Events	93
		Matilda Events	93
		Extending Matilda – DSS0102 Events	95
		Rama Events	98
		Extending Rama – S0k Events	99
		Summary	102
5.3	Densifie	cation of the Snowpack	102
	5.3.1	Density Profiles	102
	5.3.2	Density Effects on the Extended Firn Core Records	104
		<i>Season 1</i> – S0k	105
		<i>Season 2</i> – DSS0102	106
		Correcting for Densification – DSS0102	107
5.4	Concluc	ling Remarks	109
Cha	nter 6	Seasonal Characteristics of High Resolution Firn Core Signals	111
6 1	Overvie		111
6.2	Summa	rised Literature Review for Seasonality Studies of $\delta^{18}$ O and Trace Chemical	111
0.2	Species	in Antarctic Ice Cores	112
	6 <b>7</b> 1	$\delta^{18}$ O	112
	622	Marine Biogenic Sulphur Compounds	112
	623	Nitrate	112
	624	Son Salta	113
63	0.2.4 Saacona	slity of S <sup>18</sup> O and Trace Ion Species over Four Annual Cycles at Law Dome	114
0.5	( 2 1	s <sup>18</sup> O	110
	0.3.1		110
		Seasonal Cycle	110
		Temperature and $\delta^{\circ}O$	117
		<i>Cyclonic Precipitation and</i> $\delta^{\circ O}$ <i></i>	122
	6.3.2	MSA	123
		Seasonal Cycle	123

		Temperature and MSA	124
	6.3.3	Nitrate	126
		Seasonal Cycle	126
		Temperature and Nitrate	126
	6.3.4	Non-sea Salt Sulphate	128
		Seasonal Cycle	128
		Temperature and Non-sea Salt Sulphate	128
	6.3.5	Sea Salts	130
		Seasonal Cycle	130
		Wind Speed, Direction and Sea Salts	130
6.4	Sources	Regions for Seasonal Signals Preserved in Law Dome Ice Cores	133
	6.4.1	Seasonality in Atmospheric Circulation for Net Accumulation Events	135
6.5	Conclud	ing Remarks	136
	pter /	Phot Study: Examination of Three Accumulation Periods in the Rama	Snow Pit
7.1	Chamia	W	139
7.2		and isotopic Signals	140
7.5	Local M	Seele Meteorele sigel Conditions	143
/.4	Synoptic	Scale Meteorological Conditions	144
7.5	Source F	ing Demortant Presente	14/
/.0	Conclud	ing Remarks	149
Cha	pter 8	Investigation of Specific Meteorological Events Preserved in High	
		Resolution Snow Pit Records	150
8.1	Overview	w	150
8.2	Current	Seasonal Studies from Law Dome Ice Cores	151
8.3	Glaciolo	gical and Meteorological Tools	152
	8.3.1	Glaciological Tools	152
		Dating the Chemical and $\delta^{I8}O$ Records	153
		Differentiation in Dating between Pilot Study and Chapter 8	154
	8.3.2	Meteorological Tools	154
	8.3.3	Comparing Chemical and $\delta^{18}$ O Signals with Meteorological Observations	155
8.4	Meteoro	logical Conditions Across All Seasons	156
	8.4.1	Local Meteorological Conditions	156
		Summer Events	156

		Autumn Events	156
		Winter Events	157
		Spring Events	158
	8.4.2	Synoptic Meteorological Conditions	159
8.5	Summer	Events Preserved in High Resolution Snow Pits and Firn Cores	160
	8.5.1	Events that Concur with Expected Summer Chemical and Isotopic Signals	161
		$\delta^{\prime 8}O$	162
		Marine Biogenic Indicators: MSA and Non-Sea Salt Sulphate	162
		Sea Salts	163
		Nitrate	164
	8.5.2	Events that Differ from Expected Summer Chemical and Isotopic Signals	164
		Enhanced Summer Sea Salts (Events 1 and 25)	164
		Deviation Between MSA and Non-Sea Salt Sulphate (Event 21)	165
		Enhancement of Summer Marine Biological Indicators (Event 29)	166
		Low or Declining Marine Biological Indicators (Events 26 and 30)	167
	8.5.3	Concluding Remarks: Summer	169
8.6	Autumn	Events Preserved in High Resolution Snow Pits and Firn Cores	171
	8.6.1	Events that Concur with Expected Autumn Chemical and Isotopic Signals	172
		$\delta^{\prime 8}O$	173
		Marine Biogenic Indicators: MSA and Non-Sea Salt Sulphate	173
		Sea salts	173
		Nitrate	174
	8.6.2	Events that Differ from Expected Autumn Chemical and Isotopic Signals	174
		Low Autumn Sea Salts (Events 10, 11, 12, 14, 15, 37 and 51)	174
		Low Sea Salts – Slow Approach to Law Dome	175
		Low sea Salts – Low Latitude (Distant) Source Region	175
		Low Sea Salts – Coastline trajectory	176
		Enhanced Autumn Marine Biogenic Indicators (Events 16 and 17)	176
		Deviation Between MSA and Non-Sea Salt Sulphate (Event 38)	177
	8.6.3	Concluding Remarks: Autumn	178
8.7	Winter E	Events Preserved in High Resolution Snow Pits and Firn Cores	181
			100
	8.7.1	Events that Concur with Expected Winter Chemical and Isotopic Signals	182
	8.7.1	Events that Concur with Expected Winter Chemical and Isotopic Signals $\delta^{I8}O$	182 182

		Sea salts	. 183
		Nitrate	184
	8.7.2	Events that Differ from Expected Winter Chemical and Isotopic Signals	184
		<i>Enhanced Winter</i> $\delta^{18}O$ <i>(Events 5, 6, 7, 24, 46, 47 and 48)</i>	184
	<b>8.</b> 7.3	Concluding Remarks: Winter	186
8.8	Spring I	Events Preserved in High Resolution Snow Pits and Firn Cores	188
	8.8.1	Events that Concur with Expected Spring Chemical and Isotopic Signals	. 189
		$\delta^{l8}O$	189
		Marine Biogenic Indicators: MSA and Non-Sea Salt Sulphate	190
		Sea salts	. 190
		Nitrate	191
	8.8.2	Events that Differ from Expected Spring Chemical and Isotopic Signals	191
		Low Sea Salts and $\delta^{l_8}O$ (Event 2)	191
		Enhanced Spring Nitrate (Events 22, 44 and 45)	192
		Enhanced Spring Marine Biogenic Indicators (Events 31 and 43)	193
	8.8.3	Concluding Remarks: Spring	195
8.9	Conclud	ling Remarks	196
	8.9.1	Seasonal Considerations	196
		Summer	196
		Autumn	197
		Winter	198
		Spring	199
	8.9.2	Implications for Interpreting Longer Law Dome Ice Core Records	200
		Marine Biogenic Indicators: MSA and Non-Sea Salt Sulphate	200
		Sea Salts	201
		$\delta^{l^8}O$	202
		Nitrate	202
		Seasonal Variability in Meteorology	203
		Atmospheric Circulation Variability	203
Cha	pter 9	Conclusions and Recommendations for Further Research	205
9.1	Conclus	ions	205
9.2	Areas fo	or Further Research	208

Reference List		
Appendix A	Local and Synoptic Meteorological Conditions for Summer Events	224
Appendix B	Local and Synoptic Meteorological Conditions for Autumn Events	242
Appendix C	Local and Synoptic Meteorological Conditions for Winter Events	258
Appendix D	Local and Synoptic Meteorological Conditions for Spring Events	274

### List of Tables

2.1	Details of the four snow pits analysed in this research	26
2.2	Details of the thirteen firn cores analysed in this research	29
2.3	Concentrations of ions in a primary standard	36
2.4	Concentrations of six working standards	36
3.1	Mean deviations resulting from the seven line intra-pit comparison	45
4.1	Mean local meteorological conditions	86
5.1	Accumulation events preserved in Matilda	94
5.2	Accumulation events preserved in DSS0102	96
5.3	Accumulation events preserved in Rama	98
5.4	Accumulation events preserved in S0k	99
5.5	Significant events preserved in S0k and DSS0102 used as event ties	109
7.1	Intercomparison of snow pit signals and meteorological conditions	143
8.1	Details of the snow pits and firn cores used in the event scale examination	153
8.2	Summer events preserved in Law Dome snow pits and firn cores	160
8.3	Autumn events preserved in Law Dome snow pits and firn cores	171
8.4	Winter events preserved in Law Dome snow pits and firn cores	181
8.5	Spring events preserved in Law Dome snow pits and firn cores	188

### List of Figures

1.1	Simplified fractionation model for oxygen isotopes	3
1.2	Possible sources of natural sulphur preserved in polar ice	10
2.1	Location map for Law Dome	23
2.2	Location schematic for the snow pits and firn cores	24
2.3	Snow pit sampling probe and template	27
2.4	Schematic cross section of the Rama snow pit	28
2.5	Schematic cross section of the longitudinal cuts made in firn cores	30
2.6	Decontamination of a firn core sample	31
2.7	Cation separation	33

2.8	Anion separation	34
2.9	Calibration curve for sodium	35
3.1	Seven line intra-pit comparison for the <i>Rama</i> snow pit	40
3.2	Seven line intra-pit comparison for the Rama snow pit with an adjusted depth sca	e 43
3.3	Average chemical and $\delta^{18}$ O records for the <i>Rama</i> snow pit	44
3.4	Location schematic for the Rama, Karioke and Paddy snow pits	46
3.5	Inter-pit comparisons from the three snow pits	48
3.6	Location schematic for the firn cores	49
3.7	Inter-core $\delta^{18}$ O comparisons	51
3.8	Inter-core MSA comparisons	52
3.9	Inter-core nitrate comparisons	55
3.10	Inter-core non-sea salt sulphate comparisons	56
3.11	Inter-core sodium comparisons	58
3.12	Inter-core magnesium comparisons	59
4.1	Monthly air temperatures measured at Casey station and from AWS 1181	65
4.2	Daily average 4 m air temperature recorded from AWS 1181	66
4.3	Four year average temperature record	67
4.4	Tiled figure of daily average 4 m air temperatures	69
4.5	Daily average 4 m wind speed recorded from AWS 1181	70
4.6	Four year average wind speed record	71
4.7	Daily average wind direction recorded from AWS 1181	72
4.8	Four year average wind direction record	73
4.9	Correlation between wind direction and wind speed	74
4.10	Tiled figure of daily average 4 m wind speeds and wind directions	75
4.11	Daily average barometric pressure recorded from AWS 1181	77
4.12	Four year average barometric pressure record	78
4.13	Tiled figure of daily average barometric pressure	80
4.14	Total and net snow accumulation recorded from AWS 1181	82
4.15	Local meteorological conditions from AWS 1181	85
5.1	Total and net snow accumulation from AWS 1181	90
5.2	Total and net snow accumulation for Rama events	91
5.3	Total and net snow accumulation for Matilda events	92
5.4	Trace chemical and $\delta^{18}$ O signals for <i>Matilda</i> events	95
5.5	Trace chemical and $\delta^{18}$ O signals for <i>DSS0102</i> events	97

5.6	Trace chemical and $\delta^{18}$ O signals for <i>Rama</i> events	100
5.7	Trace chemical and $\delta^{18}$ O signals for <i>S0k</i> events	101
5.8	Snow pit density profiles	103
5.9	Firn core density profiles	104
5.10	MSA, sodium and $\delta^{18}$ O records preserved in <i>S0k</i>	105
5.11	MSA, sodium and $\delta^{18}$ O records preserved in <i>DSS0102</i>	107
5.12	MSA, sodium and $\delta^{18}O$ records preserved in DSS0102 corrected for densification	108
6.1	MSA, sodium and $\delta^{18}$ O records preserved in <i>DSS0102</i> corrected for densification	116
6.2	Comparison between $\delta^{18}$ O and air temperatures for <i>DSS0102</i>	117
6.3	Linear correlation of $\delta^{18}$ O values and air temperatures	119
6.4	Comparison between $\delta^{18}$ O and pressure	122
6.5	Linear correlation of $\delta^{18}$ O and pressure	123
6.6	Comparison between MSA and air temperatures	123
6.7	Correlation of MSA and air temperatures	125
6.8	Comparison between nitrate and air temperatures	127
6.9	Linear correlation of nitrate and air temperatures	127
6.10	Comparison between non-sea salt sulphate and air temperatures	129
6.11	Correlation of non-sea salt sulphate and air temperatures	129
6.12	Comparison between sodium and wind speed	131
6.13	Linear correlation of sodium and wind speeds	132
6.14	Comparison between sodium and wind direction	132
6.15	10 day back trajectories for net accumulation events	134
7.1	Total and net accumulation from 21 December 1997 to 27 February 2000	140
7.2	Chemical and $\delta^{18}$ O records from <i>Rama</i>	141
7.3	Local meteorological conditions from 1 December 1999 to 27 February 2000	145
7.4	AVHRR satellite imagery associated with net accumulation periods	146
8.1	Local meteorological conditions from 1 December 1998 to 28 February 1999	225
8.2	Local meteorological conditions from 1 December 1999 to 29 February 1999	226
8.3	Local meteorological conditions from 1 December 2000 to 28 February 2001	227
8.4	Local meteorological conditions from 1 December 2001 to 31 December 2001	228
8.5	AVHRR satellite imagery for Event 18	229
8.6	AVHRR satellite imagery for Event 19	230
8.7	AVHRR satellite imagery for Event 20	231
8.8	AVHRR satellite imagery for Event 27	232

8.9	AVHRR satellite imagery for Event 28	233
8.10	AVHRR satellite imagery for Event 41	234
8.11	AVHRR satellite imagery for Event 42	235
8.12	AVHRR satellite imagery for Event 1	236
8.13	AVHRR satellite imagery for Event 25	237
8.14	AVHRR satellite imagery for Event 21	238
8.15	AVHRR satellite imagery for Event 29	239
8.16	AVHRR satellite imagery for Event 26	240
8.17	AVHRR satellite imagery for Event 30	241
8.18	Local meteorological conditions from 1 March 1998 to 31 May 1998	243
8.19	Local meteorological conditions from 1 March 1999 to 31 May 1999	244
8.20	Local meteorological conditions from 1 March 2001 to 31 May 2001	245
8.21	AVHRR satellite imagery for Event 13	246
8.22	AVHRR satellite imagery for Event 50	247
8.23	AVHRR satellite imagery for Event 10	248
8.24	AVHRR satellite imagery for Event 11	249
8.25	AVHRR satellite imagery for Event 12	250
8.26	AVHRR satellite imagery for Event 14	251
8.27	AVHRR satellite imagery for Event 15	252
8.28	AVHRR satellite imagery for Event 16	253
8.29	AVHRR satellite imagery for Event 17	254
8.30	AVHRR satellite imagery for Event 37	255
8.31	AVHRR satellite imagery for Event 38	256
8.32	AVHRR satellite imagery for Event 51	257
8.33	Local meteorological conditions from 1 June 1998 to 31 August 1998	259
8.34	Local meteorological conditions from 1 June 1999 to 31 August 1999	260
8.35	Local meteorological conditions from 1 June 2000 to 31 August 2000	261
8.36	Local meteorological conditions from 1 June 2001 to 31 August 2001	262
8.37	AVHRR satellite imagery for Event 8	263
8.38	AVHRR satellite imagery for Event 9	264
8.39	AVHRR satellite imagery for Event 36	265
8.40	AVHRR satellite imagery for Event 49	266
8.41	AVHRR satellite imagery for Event 5	267
8.42	AVHRR satellite imagery for Event 6	268
8.43	AVHRR satellite imagery for Event 7	269

8.44	AVHRR satellite imagery for Event 24	270
8.45	AVHRR satellite imagery for Event 46	271
8.46	AVHRR satellite imagery for Event 47	272
8.47	AVHRR satellite imagery for Event 48	273
8.48	Local meteorological conditions from 1 September 1998 to 30 November 1998	275
8.49	Local meteorological conditions from 1 September 1999 to 30 November 1999	276
8.50	Local meteorological conditions from 1 September 2000 to 30 November 2000	277
8.51	Local meteorological conditions from 1 September 2001 to 30 November 2001	278
8.52	AVHRR satellite imagery for Event 3.	279
8.53	AVHRR satellite imagery for Event 4	280
8.54	AVHRR satellite imagery for Event 32	281
8.55	AVHRR satellite imagery for Event 33	282
8.56	AVHRR satellite imagery for Event 34	283
8.57	AVHRR satellite imagery for Event 35	284
8.58	AVHRR satellite imagery for Event 2	285
8.59	AVHRR satellite imagery for Event 22	286
8.60	AVHRR satellite imagery for Event 31	287
8.61	AVHRR satellite imagery for Event 43	288
8.62	AVHRR satellite imagery for Event 44	289
8.63	AVHRR satellite imagery for Event 45	290