Clim Dyn (2011) 36:1403–1417
DOI 10.1007/s00382-010-0892-1

The effect of Antarctic sea ice on the Southern Hemisphere atmosphere during the southern summer

M. N. Raphael · W. Hobbs · I. Wainer

Received: 21 August 2009 / Accepted: 29 July 2010 / Published online: 12 August 2010

Abstract This study examines the influence of Antarctic sea ice distribution on the large scale circulation of the Southern Hemisphere using a fully coupled GCM where the sea ice submodel is replaced by a climatology of observed extremes in sea ice concentration. Three 150-year simulations were completed for maximum, minimum and average sea ice concentrations and the results for the austral summer (January–March) were compared using the surface temperatures forced by the sea ice distributions as a filter for creating the composite differences. The results indicate that in the austral summer the polar cell expands (contracts) under minimum (maximum) sea ice conditions with corresponding shifts in the midlatitude Ferrell cell. We suggest that this response occurs because sea ice lies in the margin between the polar and midlatitude cells. The polarity of the Southern Hemisphere Annular (SAM) mode is also influenced such that when sea ice is at a minimum (maximum) the polarity of the SAM tends to be negative (positive).

1 Introduction

While sea ice is a fundamental feature of the Antarctic climate, it has often been regarded as a passive rather than an active agent in climate processes, hence, research has tended to focus on the response of the sea ice to atmosphere or ocean forcing. Normally, the relationship between sea ice and the atmosphere is explained mostly in terms of local scale atmosphere and ocean dynamics and thermodynamics (e.g. Zhang 2007; Liu et al. 2004; Deser et al. 2000, Sen Gupta and England 2006; Holland et al. 2005, Raphael 2007; Stammerjohn et al. 2008; Yuan and Li 2008). These studies, among others, make clear the pivotal role that both the atmosphere and the ocean play in the formation and maintenance of sea ice. However, once present, sea ice can and does exert a strong influence on its environment. Its high albedo reduces the amount of shortwave radiation that can be absorbed by the surface (thereby reducing the surface temperature) and the ocean. It also limits the vertical exchange of heat and moisture between the ocean and the atmosphere (Maykut 1986). The net effect of this is to modify the radiative, energy and mass exchange process in the southern high latitudes. Sea ice also has the potential to redirect surface currents and to change the rates at which the surface water subsides at Antarctic latitudes. Since sea ice anomalies tend to persist for several months they have the potential for strongly affecting the atmospheric and oceanic circulation (e.g. Lemke et al. 1980).

Among the observational studies showing a relationship between Antarctic sea ice and the Southern atmosphere are Cavalieri and Parkinson (1981), Carleton (1981, 1988), Simmonds and Jacka (1995), Yuan and Martinson (2001), Kwok and Comiso (2002) and Raphael (2007). They have uncovered links between the atmosphere and sea ice that vary in scale from synoptic to planetary scales. ENSO has been shown to have a definitive impact on ice extent and variability while Antarctic sea ice extent co-varies with a number of remote climate variables such as tropical Pacific precipitation. Even with adequate observations it is difficult to determine cause and effect since the observed data represent the combined input of all contributors to climate

M. N. Raphael (✉) · W. Hobbs
Department of Geography, UCLA, Los Angeles, USA
e-mail: raphael@geog.ucla.edu

I. Wainer
University of Sao Paulo, Sao Paulo, Brazil

and these relationships are not necessarily linear. Atmosphere/sea ice interaction is modulated by the ocean via the ocean currents and SST, ocean/atmosphere and ocean/sea ice sensible and latent heat flux exchanges, among other processes.

Modeling provides one way of testing to see the impact of sea ice on the atmosphere and ocean and this has been done for the Southern Hemisphere. Early studies of this kind have shown strong, physically consistent, atmospheric responses to sea ice, but interpretation of their results have been limited by unrealistic assumptions of sea ice amounts and variability as well as by the limitations of earlier GCM parameterizations of sea ice attributes (Walsh 1993). However, the studies show that changes in Antarctic sea ice have a significant effect on the heat fluxes and on surface temperature. A reduction in sea ice extent (SIE) produced changes in the sensible heat flux with subsequent substantial atmospheric warming (e.g. Simmonds and Budd 1991; Mitchell and Senior 1989; Bromwich et al. 1998). The surface westerlies and easterlies were also affected as was the number of cyclones close to Antarctica (Simmonds and Wu 1993).

Realistic sea ice amounts have been used by Hudson and Hewitson (2001) who found that apart from an increase in surface temperature (with reduced SIE) the Hadley cell circulation strengthened and moved south. Raphael (2002, 2003), showed that the SH atmosphere is sensitive to extremes of sea ice concentration (SIC) and that the indications of this sensitivity extend to middle and lower latitudes. More specifically, that research suggested that in summer, maximum SIC forces weaker surface winds in the midlatitudes in summer while under minimum SIC conditions the winds are stronger. These variations in the surface westerlies represent the lower atmosphere manifestation of the Southern Hemisphere Annular Mode (SAM). Hall and Visbeck (2002) in their modelling study of the SAM, associate the weaker westerlies with a southward expansion of the subtropical high and a weaker subpolar gyre.

The two studies cited above have different foci but their information suggests that sea-ice variations can have a detectable impact on the large scale atmospheric circulation. This information, although valuable, cannot effectively address the impact of sea-ice on the ocean because of their design. The relationship between sea ice and the atmosphere is non-linear and within this context one study does not provide enough information because it is too short and the other cannot effectively isolate the influence on sea-ice from that of other climatic variables.

It seems clear that sea ice has an influence on climate. However, questions about how this is achieved and the size and extent of this influence remain. In the research discussed in this paper, we examine the interaction between the large scale atmospheric circulation and the Antarctic sea ice distribution on the interannual time scale. In particular, we examine the simulated impact of satellite-observed sea ice extremes on the extratropical circulation. This impact is first seen in the surface temperatures at subpolar latitudes, which in turn influence the large scale, meridional, temperature and pressure gradients, and is transferred to the atmosphere via the surface fluxes of latent and sensible heat.

This current research may be seen as an extension of Raphael (2003) which used the National Center for Atmospheric Research (NCAR) Climate System Model (CSM1) in a multi-year experiment where the atmospheric circulation was forced by observed SIC extremes. However, those were 10-year simulations and while useful information was gleaned, questions such as the impact of the sea ice on the ocean and the role of the sea ice in the longer term variability of the atmosphere could not be addressed. In this paper, for reasons outlined below, we address the interaction of sea ice with the atmosphere only. The current experiment was run for 150 years and in this paper the atmospheric responses to sea ice concentration for summer are discussed. Section 2 describes the model and the experiment. Section 3 describes and discusses the results and Sect. 4 summarizes the results and conclusions.

2 Climate model, data and experiment design

2.1 Climate model description

The model used in these experiments is the NCAR Community Climate System Model Version Three (CCSM3) (Collins et al. 2006). This model has been used in a variety of studies. The Model's representation of the Southern Hemisphere's large scale atmospheric circulation and its variability has been thoroughly evaluated. The spatial and temporal characteristics of the large scale, surface and mid tropospheric circulation (e.g. the SAM and zonal wave 3, the semi-annual oscillation) are reasonably well simulated (e.g. Raphael and Holland 2006).

The CCSM3 has four component models—ocean, atmosphere, land and sea ice—that correspond with each other via a flux coupler (Bryan et al. 1996). The modular structure of the CCSM3 allows the user to replace the sea ice component model with, in this case, satellite-derived Antarctic sea ice concentration climatologies while the ocean, atmosphere and land submodels remain active. Information among the atmosphere, land and sea ice submodels is exchanged on an hourly basis while with the ocean submodel the time step is daily. The experiment is run at a spectral resolution of T42 (approximately $2.8° \times 2.8°$). The atmosphere has 26 vertical levels and the ocean 40. A smaller scale experiment using the same method with an earlier version of the model was successfully completed by Raphael (2003). That model worked well, producing physically plausible results on seasonal to interannual time scales.

There are a number of similarities between this experiment and that reported on by Raphael (2002, 2003). However this experiment differs, particularly in the length of the simulation which is 150 years. The earlier simulations ran for only 10 years so that variation at longer time scales in the ocean was not an important factor. In the current experiment where the ocean is active and is allowed to respond to the atmosphere through the sea ice leads and along the ocean/sea ice margin, the role of the ocean becomes very important over a simulation of 150 years. Like the earlier experiment surface temperature responses within the domain of the sea ice are expected to be due to the sea ice differences while those farther afield are expected to be due to large scale dynamic adjustments. The prescribed sea ice distributions potentially present the model with a perturbation that is not internally consistent with its physical state and the ocean model's response typically would be to try and remove that perturbation. This could mean that the ocean would try to create more ice than exists in the minimum scenario or less ice than exists in the maximum scenario. It is possible that the SST at the ice/ocean boundary may be too warm or too cold to support the SIC. In that case if the SST of a preceding month is too cold to support an ice-free zone the ocean temperature is brought to freezing point in the regions where there is no prescribed sea ice and allowed to form ice in regions where there is ice in the climatology. Brine rejection, an important part of the process in the formation of sea ice and in the development of Antarctic Bottom Water and therefore the thermohaline circulation, will occur. This is particularly important for longer term simulations such as the ones described here. If, however, the SST of the preceding month is too warm to support an ice-covered ocean then the ocean will melt ice and the water at the surface will freshen but the SIC will remain as prescribed. As designed, this experiment isolates the impact of ice on the atmosphere by not allowing the ocean to contribute to this impact beyond the limits of that set by the sea ice distribution. The ocean atmosphere feedback is potentially not allowed to develop fully. This has direct consequences for interpretation of the ice on ocean impact and also influences the degree of ocean atmosphere exchange. These are limitations that occur if impacts are to be isolated, however, it allows the results to be seen more clearly as a response of the atmosphere to sea ice.

2.2 Data and experiment design

This study uses satellite-observed sea ice with the expectation that realistic sea ice conditions facilitate interpretations of the results, and also to attempt to match closely conditions that would exist in reality. The sea ice concentration (SIC) dataset used to construct the minimum, maximum and average climatologies used in the simulations is the Met Office Hadley Centre's sea ice and sea surface temperature (SST) data set, HadISST1 (Rayner et al. 2003). This dataset is a combination of monthly globally complete fields of SST and sea ice concentration on a 1° latitude–longitude grid. Pre-satellite era, observed, SIC are made consistent with the satellite data. The accuracy and quality of this dataset are comparable to other published datasets and it captures well the trends in global, hemispheric, and regional sea surface temperatures. More details on this dataset can be found in Rayner et al. (2003).

Variability in sea ice concentration around Antarctic is not homogenous, in fact there are strong regional differences in sea ice trends. Some of this is a response to lower latitude forcing while some is due to higher latitude oceanic and atmospheric forcing. The aim of this study is to see how the sea ice field as a whole influences the atmosphere so we define the extremes of sea ice using its global distribution around Antarctica.

The total areal extent of the monthly mean SIC was compared to determine the months with the least sea ice and the most sea ice for the Antarctic region as a whole. The daily data for these months were then chosen for use in the simulations. Daily data were used in order to capture existing polynyas since the brine rejection process is strongly associated with polynyas and the latter can form and disappear on time scales of less than a month. Each of the 12 months in the maximum climatology (MAX) is that month in the dataset when maximum SIC values were observed. That is, the January SIC used in the maximum climatology is the January that had the greatest areal coverage of SIC during the period 1978–2000 and so on. Since the months were chosen from different years the sea ice at the beginning and end of each month were interpolated to ensure a smooth transition from one month to the other. The minimum climatology (MIN) was constructed in the same way as the maximum climatology but for minimum areal coverage of sea ice. The average climatology (CON) is the simple daily average SIC calculated over the period 1978–2000.

Figure 1 shows the summer [January, February, March (JFM)] differences in sea ice. In the MAX sea ice is generally greater than that in the MIN and CON climatologies. However, the SIC differences are not homogeneous in sign, ranging in size from +50 to −20%. The largest positive difference, with respect to the mean (CON) exists in the eastern Weddell and Ross seas. Elsewhere, there is little to no difference between the CON and MAX except in the Bellingshausen–Amundsen (BA) Seas where SIC is smaller in the MAX scenario. By comparison, the difference

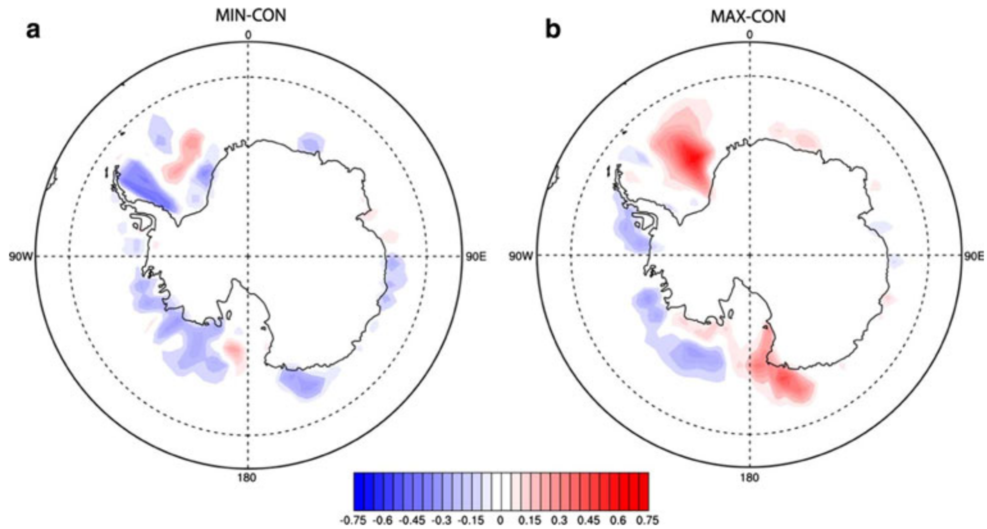

Fig. 1 Summer (JFM) sea ice concentration distribution. **a** MIN–CON and **b** MAX–CON. Units are in %

between the MIN and CON SIC climatologies (Fig. 1a) is mostly homogeneous—MIN is usually less than CON except for small areas in the Weddell and Ross seas. The differences between MIN and CON (not shown) show that MAX is generally always greater than MIN. The differences in Fig. 1 are small but small differences in sea ice concentration and sea ice extent have been associated with large scale changes with the atmospheric circulation (Raphael 2003, Yuan and Martinson 2001). It is notable that the largest differences occur in regions of strong interannual sea ice variability—the Weddell and Ross Seas (e.g. Cavalieri et al. 1999)—suggesting that the distributions used capture some of the variability in sea ice. The differences in sea ice for both scenarios for the eastern Antarctic are small but this region has much less ice compared to the Weddell and Ross Seas and the variability is smaller than in the west Antarctic (Cavalieri and Parkinson 2008). Sea ice variability in west Antarctica, in the region between and including the Weddell and Ross Seas, is strongly influenced by the large scale extra-polar circulation (e.g. Kwok and Comiso 2002; Carleton 2003; Liu et al. 2004; Raphael 2007) and may be key to modulation of the Antarctic climate.

Three 150-year simulations were run, one each with a different sea ice climatology. The simulations branched off year 400 of the 1,000 year control run of the CCSM3 (Collins et al. 2006). This point in the control simulation was chosen because it represented the beginning of a period of reduced variability, lasting for more than 150 years, in the 1,000 year control run. The rationale here was that this was a stable period in the control simulation and therefore there was a reduced chance of internal model variability influencing the outcomes of the experiments.

3 Results and analysis

3.1 Area weighted surface temperature index

Normally, in experiments such as these, the full mean composites of the variables of interest would be calculated and difference plots made to see if and where the simulated variables from, say, MAX were significantly different from those of CON. For these experiments these composites were calculated and it was found that the time mean differences among the three scenarios were quite weak and not statistically significant, suggesting that sea ice had little or no impact on the large scale circulation. However, further examination of the temporal variation of several key variables such as the zonal wind and geopotential height revealed significant short (interannual) and longer term (interdecadal) fluctuations. The nature of the latter meant that the time means and their differences were small. Plots of primary atmospheric variables at extrema in these longer term fluctuations (not shown) showed significant differences between the scenarios that were ultimately reduced in the averaging process. We believe that the long term fluctuations maybe due to the influence of the ocean and some further simulations have been carried out to explore that influence. We do not report on those here. Instead our analysis in this paper uses the surface temperature forced by sea ice as a filter for determining the impact of the sea ice on the large scale atmosphere at the interannual timescale.

The analysis is carried out from the point of view that, through its insulating effect, the sea ice distribution has a direct influence on the surface temperature. Changes in surface temperature have a direct effect on lower atmospheric buoyancy which in turn affects the atmospheric

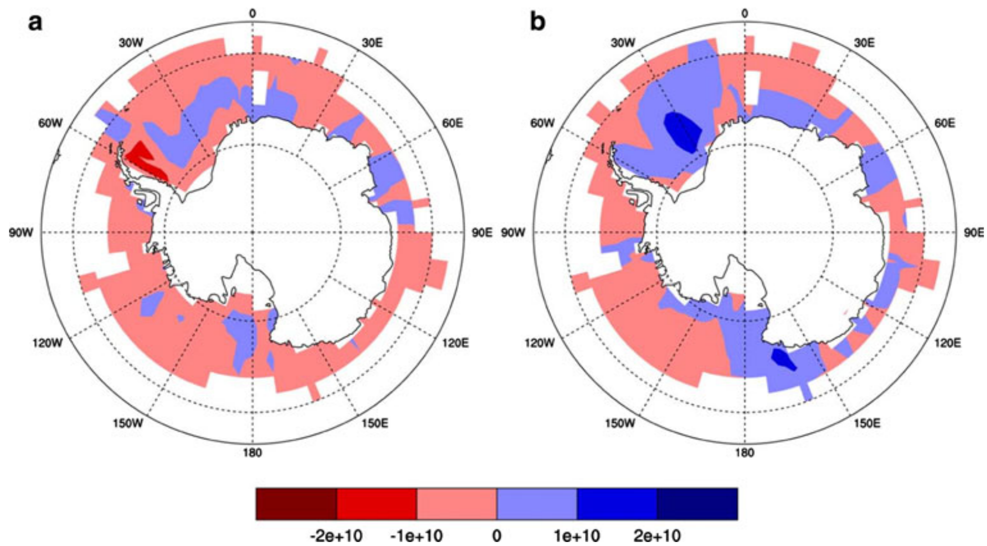

Fig. 2 Areal difference in summer (JFM) sea ice fraction. **a** MIN–CON and **b** MAX–CON

pressure surfaces and the meridional temperature and pressure gradients. The sea ice effect on temperature is transferred from the surface to the atmosphere by the radiative and turbulent energy fluxes. To determine the impact of the sea ice distribution on surface temperature, we first created an areally averaged weighted surface temperature index.

To create the index the difference in ice fraction for the whole ice field for each of the scenarios was calculated: MIN–CON, MAX–CON and MIN–MAX. This difference was then multiplied by the grid square area (m^2) to give the difference in m^2 of ice-free ocean between the extreme SIC and the average (CON) simulations. Like the ice fraction differences, the areal differences (Fig. 2) are not homogeneous but is clear that in the MIN (Fig. 2a) the area occupied by sea ice is much less than in the CON. The reverse is true for the MAX (Fig. 2b) especially in the Weddell and Ross Seas but the areal differences are not as large. This areal difference was then used as the weighting function to create a time series of weighted areal average temperature (Fig. 3). Although the difference in area has polarity i.e. some areas are negative, e.g. where area covered by ice in CON is greater than that in MIN, only the absolute values were used for the weighting function. This means that the differences may be damped.

The temperature time series for the simulations and their differences (Fig. 3) represent the weighted average surface temperature in the region where there is a difference in SIC between the scenarios. Note that the temperature series for CON is different for the two scenarios. This is because the temperature in the regions where differences in SIC occur between MIN and CON are different to the temperatures in the region where differences in SIC are found between MAX and CON. The temperature time series display three key characteristics.

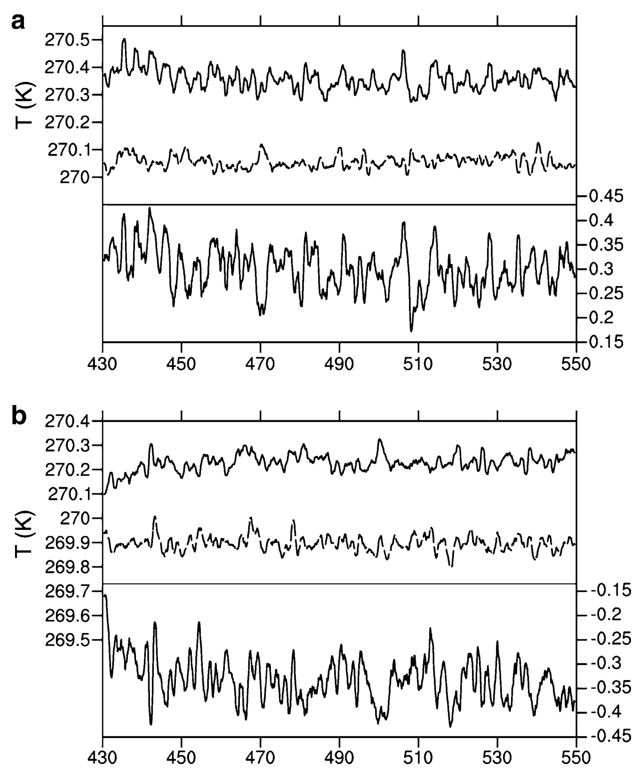

Fig. 3 Area-weighted temperature time series for summer (JFM) **a** MIN, **b** MAX and CON (*dashed line*) and their difference MIN–CON, MAX–CON. Units are in K

1. It is always warmer under MIN conditions and cooler under MAX conditions than under CON conditions. This thermodynamic response is expected since the presence of ice would foster lower temperatures and vice versa.
2. The differences between the perturbations and the control are very small, never more than half a degree. This is partly a result of damping due to the use of

absolute differences; regional differences may be larger. The small size of the differences may also indicate that the system is very finely balanced and small changes can have large impacts.

3. There is strong interannual to longer term variability apparent in all three simulations and there is no sustained trend. The interannual variability in surface temperature might represent fluctuations internal to the atmosphere–ocean system since they occur in all of the simulations. It is possible that the longer term variability involves some adjustment by the ocean and that is being investigated separately.

3.2 Composite difference in climate variables

The results discussed here focus on the differences between the simulations on the interannual time scale. To obtain a sense of the atmospheric response to the different sea ice scenarios, the significant atmospheric variables—zonal wind (U), geopotential height (Z3), vertical motion (OMEGA), temperature (T), sea level pressure (SLP)—were composited based on the weighted temperature differences (Fig. 3) between the CON and the MAX and MIN scenarios that were one standard deviation away from the mean difference. In this way, we compare the atmospheric responses at times when the temperatures were warmest in the MIN (compared to the CON) and coolest in the MAX (compared to the CON) so that the impact of the sea ice-driven surface temperatures, if any, would be maximized. This approach is chosen because the longer term variability exhibited in the time series renders the time-mean response very small. The composite differences are described below.

3.2.1 Temperature

The temperature distribution of the CON is shown in Fig. 4a and is evidence that the simulation captures the important elements of the 850 hPa temperature surface. It is concentric around the South Pole and ranges from 264 K at the Antarctic continental boundary to 296 K over the three other southern continents. The differences between the average and extreme sea ice simulations indicate that in the MIN (Fig. 4b) scenario it is warmer around Antarctica poleward of 60°S than in the CON. This is consistent with the smaller SIC shown in Fig. 1a and the areal difference in sea ice shown in Fig. 2a. The warmest area is approximately 1°C warmer, lies within the Ross Sea and extends north into the Pacific Ocean. In the middle latitudes over the oceans it is cooler in the MIN. These cooler regions extend from the southeast Atlantic across the southern

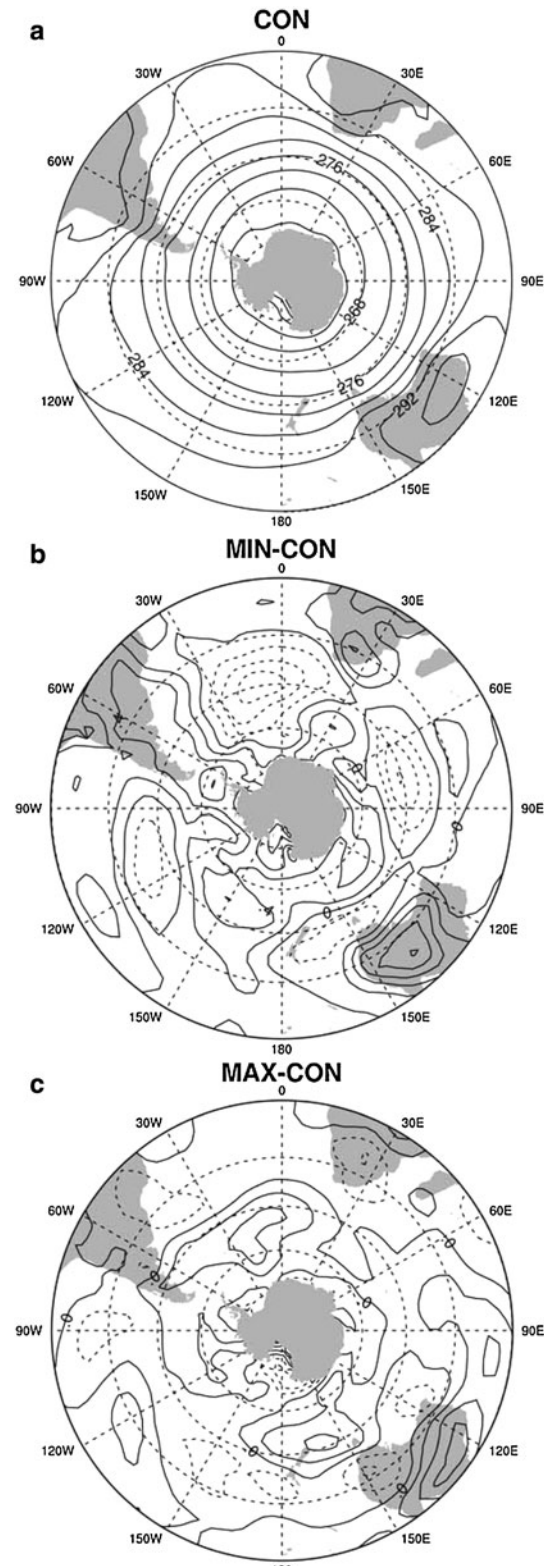

Fig. 4 Summer (JFM) 850 hPa temperature. **a** Long term average–CON and composite differences, **b** MIN–CON, and **c** MAX–CON. Contour interval in **a** is 4, and 0.2 in **b** and **c**. Units are in K

Indian Ocean and to the south and east of Australia. Australia itself, the subtropical continents and the northern Indian Ocean are warmer in the MIN scenario. Overall, this pattern of differences suggests a local influence around Antarctica coupled with large scale effects further north.

The differences between MAX and CON (Fig. 4c) exhibit a pattern that in many respects is the opposite of that shown in Fig. 4b. It is less well-organized, perhaps because the areal differences in sea ice and therefore temperature are not as pronounced as in MIN–CON. Temperatures are lower close to the continent, lowest in the Ross Sea. North of this region the difference between MAX and CON tend to be negative where the differences between MIN and CON were positive.

These 850 hPa temperature differences match the SIC differences such that it is warmer where there is less ice and cooler where there is more. The larger differences occur close to the continental edge but, notably, they extend well north of the region of summer sea ice. The differences in temperature close to the continental edge may be reasonably explained as a direct thermal response to the sea ice distribution. Lower SIC (in the MIN) means a reduced albedo, more absorption of shortwave radiation—especially important in the summer period of high sun—warmer surface ocean temperatures and subsequent stronger flux of heat from the ocean to the atmosphere. The reverse argument can be made for more sea ice—in the MAX. However, the coherent differences that occur further afield indicates that there maybe some indirect dynamic adjustment.

The temperature differences that are seen at the surface extend through the depth of the troposphere and reach a maximum in the middle troposphere (Fig. 5). This is a clear indication that the impact of the distribution of sea ice on temperature is not limited to the surface. Under the MIN scenario (Fig. 5a) it is warmer poleward of 50°S, and peak differences occur in the mid troposphere (500 hPa) where the difference is as much as 0.8°C. Between 35°S and 50°S temperatures are cooler by as much as 0.3°C whereas equatorward of 35°S temperatures are warmer reaching a maximum near 25°S. The pattern of differences in the MAX–CON (Fig. 5b), while smaller in magnitude, is approximately the opposite of MIN–CON. One noticeable difference is that the cooler temperatures poleward of 60°S in MAX peak near 300 mb compared to the warming in MIN.

The temperature response suggests a reduction of the mid/high latitude temperature gradient in the MIN and a strengthening of the same gradient in the MAX. Examination of the 65°S–40°S temperature gradient for all three simulations confirm this. Such large scale changes in the temperature gradient, while promoted by the surface temperatures forced by the sea ice distribution, must be supported by large scale circulation responses as is discussed below.

3.2.2 Atmospheric pressure

SLP in the extratropics is dominated by the subtropical highs and the circumpolar low, as illustrated in Fig. 6a. The results shown in Fig. 6b and c suggest that sea ice distribution in the MAX and MIN simulations influences the magnitude of atmospheric pressure in region of the circumpolar low so that the low is deeper (negative differences) in the MAX and shallower (positive differences) in the MIN with respect to the CON. Further north there are also significant, coherent, and opposing differences in the MIN and MAX simulations. Extending from the subtropics to the midlatitudes SLP is lower in the MIN. The opposite is true of the MAX, except over the Indian Ocean, but the values are smaller and the latitudinal range is also smaller.

As found for temperature, the pattern of sea level atmospheric pressure differences extend through the depth of the troposphere (Fig. 7); maximum differences occur near 200 hPa. The zonally averaged data show that the largest positive differences between MIN and CON

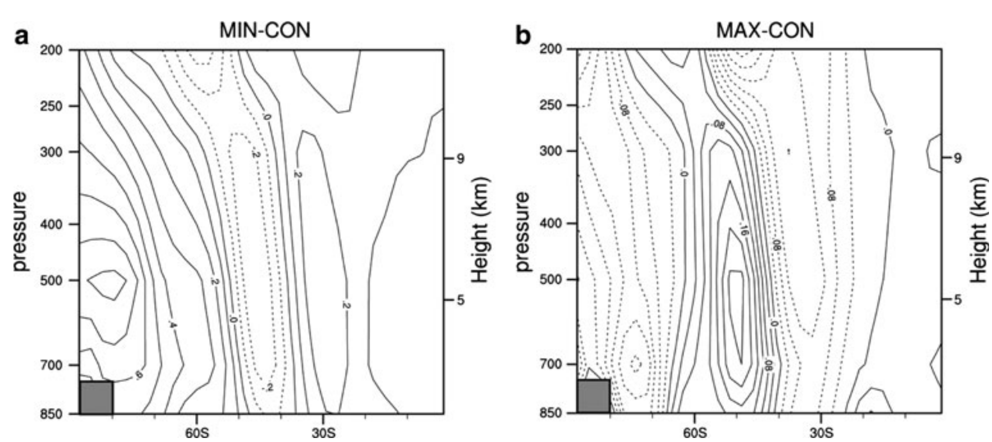

Fig. 5 Summer (JFM) hemispheric zonally averaged vertical distribution of composite temperature differences. **a** MIN–CON and **b** MAX–CON. Contour interval is 0.1 in **a** and 0.04 in **b**. Units are in degrees K

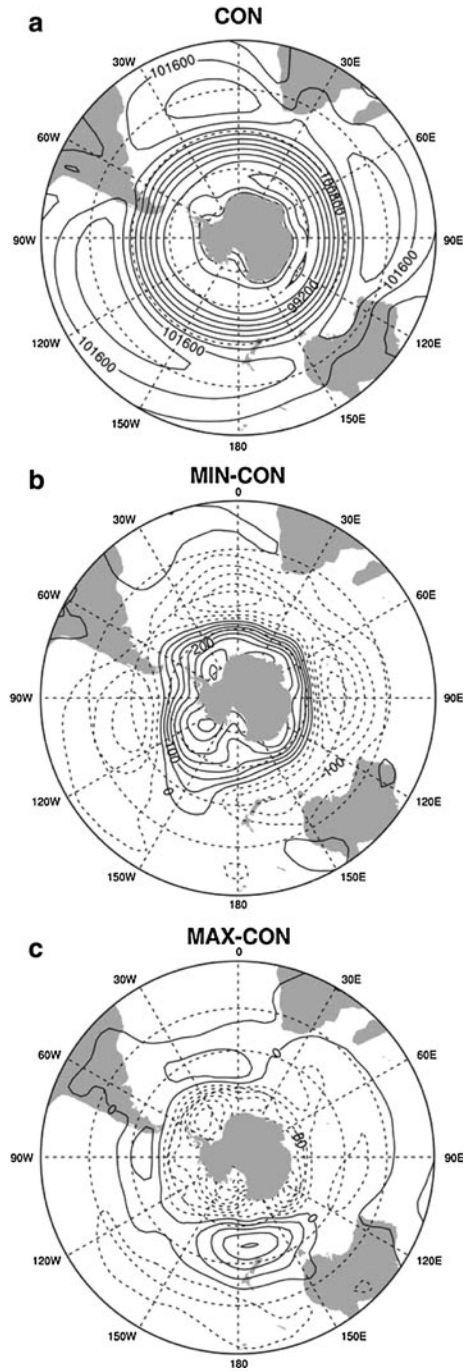

Fig. 6 Summer (JFM) sea level pressure. **a** Long term average CON and composite differences, **b** MIN–CON and **c** MAX–CON. Units are in hPa

(Fig. 7a) are found south of 55°S over Antarctica while the negative differences are found in the middle latitudes, 30–60°S. Between MAX and CON (Fig. 7b) the differences are much smaller but the pattern is coherent. The reduced mid/high latitude meridional temperature gradient suggested in Fig. 4b coincides well with the apparent relaxation of the meridional pressure gradient.

The overall impression given by Figs. 6 and 7 is that the mid-high latitude pressure gradient is influenced by SIC such that when there is more sea ice (cooler surface temperatures) the gradient is steeper and when there is less sea ice (warmer surface temperatures) the gradient is shallower. The changes in the meridional pressure gradient are consistent with the meridional temperature gradient discussed above; the shallower (steeper) temperature gradient of the MIN (MAX) coincides with the apparent relaxation (steepening) of the meridional SLP gradient. Such an association may be explained in terms of the energy flux from the ocean surface to the atmosphere. The warmer surface conditions that occur under reduced sea ice (MIN) results in an increased flux of energy (latent and sensible) from the ocean to the lower atmosphere with consequent increase in temperature in the lower layers. The warmed air becomes more buoyant, the pressure surfaces lift and as a consequence the meridional pressure gradient decreases. On the other hand, if energy transfer from the ocean to the atmosphere is restricted by sea ice (as in the MAX), the flux of heat from ocean to atmosphere will be significantly reduced. The surface will also be cooler because of the higher albedo, and the lower layers of the atmosphere will also be cooler and less buoyant. As a result, the meridional pressure gradient would steepen.

We note that if the flux of energy from ocean to atmosphere were to continue then the ocean surface should cool and the vertical flux will decrease—a negative feedback. Under minimum SIC this negative feedback is not allowed because the sea ice distribution and therefore the temperature associated with it is not allowed to change. The atmosphere then remains more buoyant than in the CON or the MAX. Note that if the SIC were allowed to respond then the MIN sea ice conditions would maintain a neutrally stable atmospheric state in the absence of other forcing factors.

3.2.3 Zonal wind

The CON composite of the zonal wind (U) at 1,000 hPa (Fig. 8a) show the polar easterlies, the westerlies and the subtropical easterlies quite clearly. The strength and spatial domain of these winds correspond well with observations. In the MIN–CON (Fig. 8b), easterly wind speeds are stronger from 60°S to the continent. This is the result of an equatorward expansion of the region occupied by the polar easterlies and an increase in the speed of easterly winds at high latitudes. At mid latitudes, between 45°S and 60°S the westerly winds are weaker in MIN. The peak reductions lie near 60°S where it reaches -1.6 m s^{-1}. Further north, from 30° to 45°S, westerly wind speeds are stronger in MIN, reaching a maximum difference of 0.8 m s^{-1} over the ocean near southeastern Australia. The pattern of

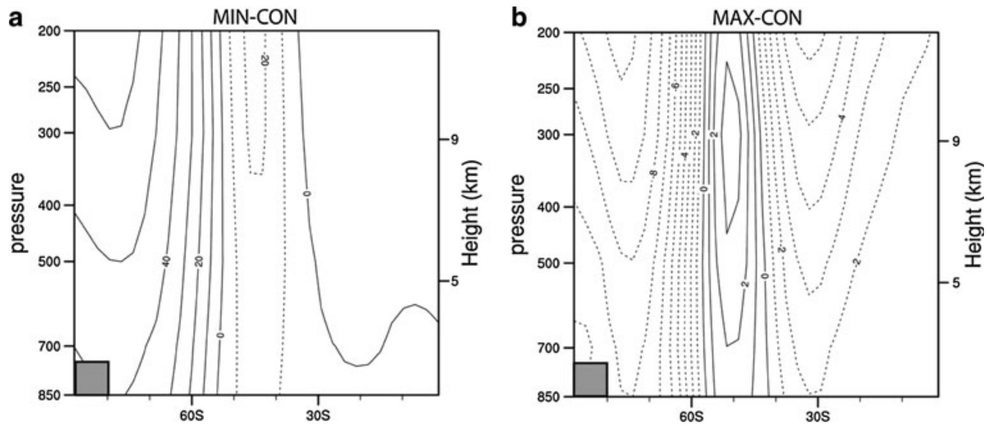

Fig. 7 Summer (JFM) hemispheric zonally averaged vertical distribution of composite pressure differences. **a** MIN–CON and **b** MAX–CON. Units are in hPa

differences between the MAX and CON (Fig. 8c) although less well-organized, is the reverse of what is shown for MIN–CON and their magnitude is smaller. The polar easterlies are weaker in a reduced spatial domain, and the westerlies from 30° to 45°S are also weaker, except over the southern Indian ocean. Stronger westerlies occur from 45° to 60°S.

The zonally averaged zonal wind (Fig. 9a) displays the single upper tropospheric midlatitude jet with core speed of 40 m s^{-1} that is characteristic of the southern summer circulation. More striking, is the well defined pattern of alternating positive and negative differences between MIN and CON, and also MAX and CON, ranging from −2.25 to 1.5 m s^{-1} (Fig. 9b, c). These correspond well to the spatial difference patterns shown in Fig. 8b and c. In MIN–CON, stronger winds occur in the middle troposphere over the continent while from 45°S to 70°S winds are weaker, weakest near 250 hPa and this extends into the stratosphere. Stronger winds occur from 30°S to 40°S also peaking near 250 hPa while weaker winds occur above the surface (near surface easterlies are stronger in CON) from 25°S to the equator. This alternating pattern of weaker and stronger winds suggest an equatorward shift in the circulation so that the effect of the smaller sea ice concentration is a general weakening of the circulation accompanied by an equatorward shift of about 2°. The core of the jet stream is more expanded in MIN (not shown) than CON indicating a relaxation of the jet associated with the gentler pressure gradient suggested by Fig. 7a. Assuming that angular momentum is conserved as the jet widens it should slow down (e.g. Monaghan and Fyfe 2006). In the MIN the peak strength of the jet remains unchanged and its equatorward shift dominates any changes in wind speed.

Compared to the CON the core of the jet in the MAX (not shown) is smaller, suggesting a contraction in response to the steeper pressure gradient. The differences in wind speed are smaller and of opposite sign to that between MIN and CON, ranging in size from −1.4 to 1.4 m s^{-1} (Fig. 8c). The pattern of alternating differences in this case suggest a poleward shift of the circulation which also dominates any changes in wind speed.

The responses of the zonal circulation to the sea ice distributions appear linked to the different meridional temperature and pressure gradients forced by the SIC. They are also integrated by the large scale meridional circulation as demonstrated by OMEGA, the vertical velocity (Fig. 10). Figure 10a shows, for reference, the vertical motion simulated in the CON. Clearly seen is the strong uplift in the Hadley Cell, descent in the subtropical high and the weaker uplift associated with the Antarctic polar frontal zone. Also apparent is a zone of descent over Antarctica associated with the Polar Cell. Alternating pattern of differences between MIN and CON (Fig. 10b) suggest that there is an equatorward shift in the zones of uplift and descent, corresponding closely to what the zonally averaged zonal winds show in Fig. 9b. For example in Fig. 10b, MIN–CON, the center of the zone of uplift associated with the polar cell shifted from around 60°S to lie closer to 50°S. In MAX–CON (Fig. 10c) these differences are not as well-defined although they do suggest a shift of the circulation toward the South Pole. We note that the circulation appears stronger in the MIN but maintain that this is mainly due to the shift of the circulation rather than an in situ increase. This response in the vertical velocity reinforces the idea that sea ice distribution can have an effect on the circulation beyond the local scale thermodynamic impacts.

We offer an explanation for how these responses can occur using the MIN simulation as an example. Antarctic sea ice advances and retreats in the circumAntarctic region that coincides with the subpolar frontal zone; the margin between the Polar and midlatitude cells (Fig. 11). When the temperature and pressure are consistently increased due to the reduction of sea ice in that region in the model, the region of uplift expands latitudinally. The polar cell as well as the region dominated by the surface easterlies expands with it. Subsequently the midlatitude cell is displaced equatorward with the concurrent shift of the zonal winds.

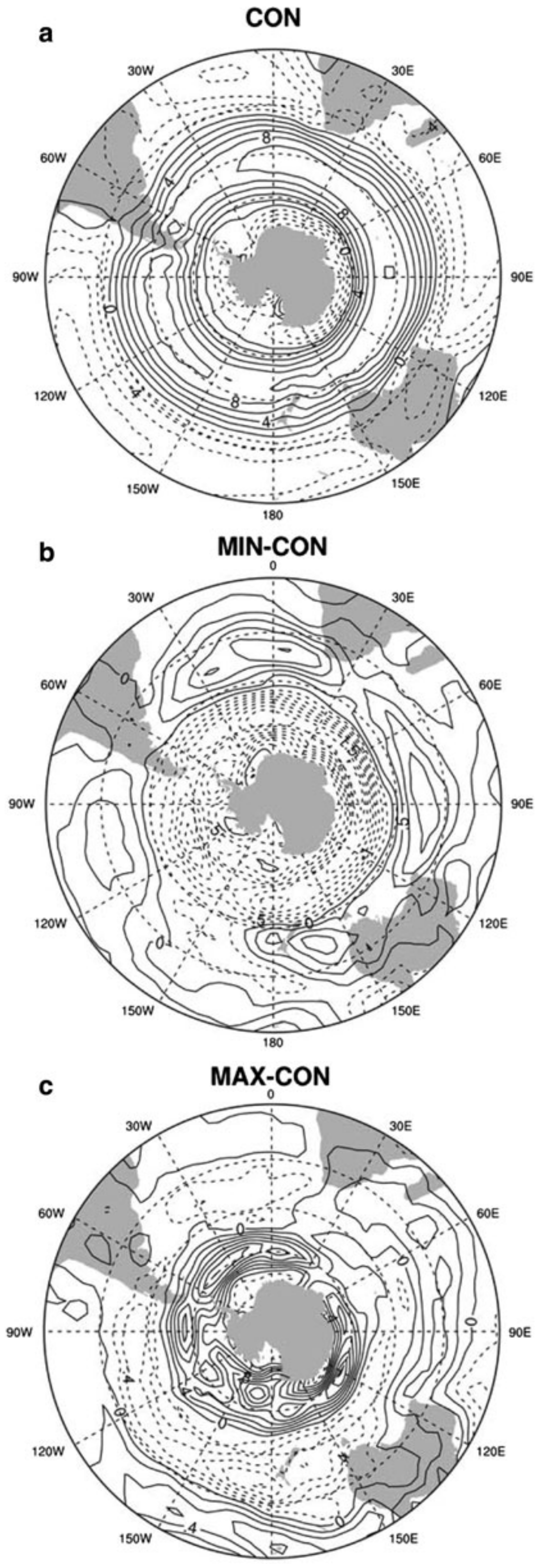

Fig. 8 Summer (JFM) zonal wind at 1,000 hPa. **a** Long term average CON and composite differences, **b** MIN–CON and **c** MAX–CON. Contour interval is 2 in **a**, 0.5 in **b** and 0.4 in **c**. Units are in meters per second

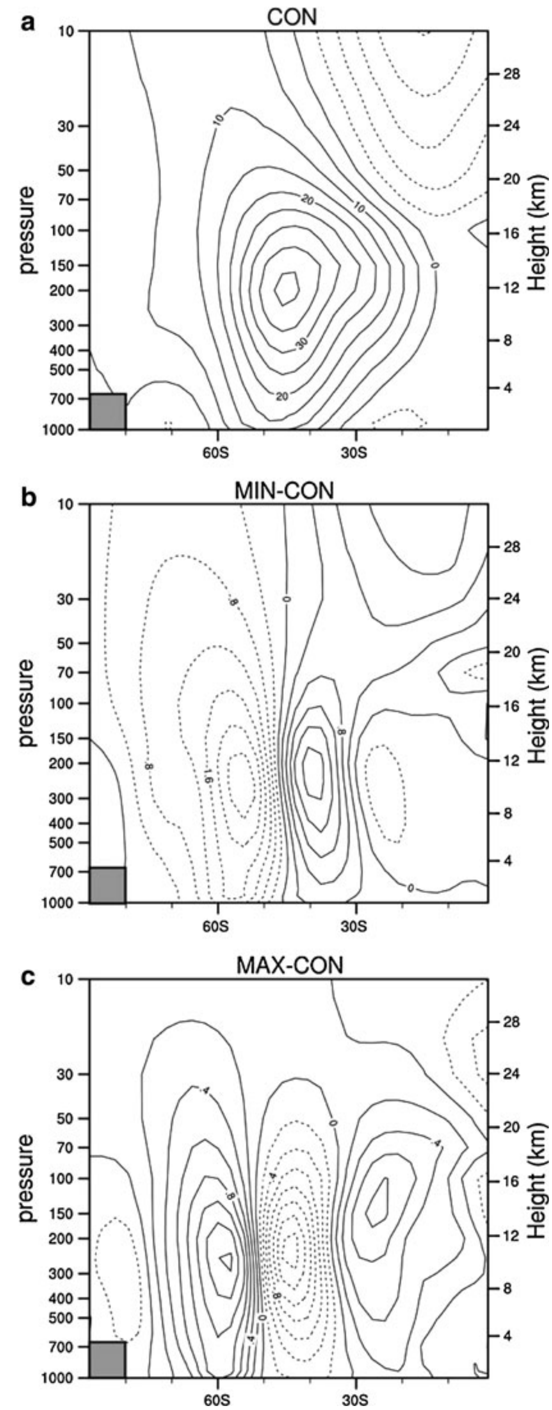

Fig. 9 Summer (JFM) hemispheric, zonally averaged wind. **a** Long term average CON and composite differences, **b** MIN–CON and **c** MAX–CON. Contour interval on MIN–CON is 0.4 and on MAX–CON it is 0.2. Units are in meters per second

When SIC is consistently larger than average, as occurs in the MAX, the reverse logic applies, as also shown in Fig. 11. This response in the polar and midlatitude cells explains how relatively small changes in temperature can

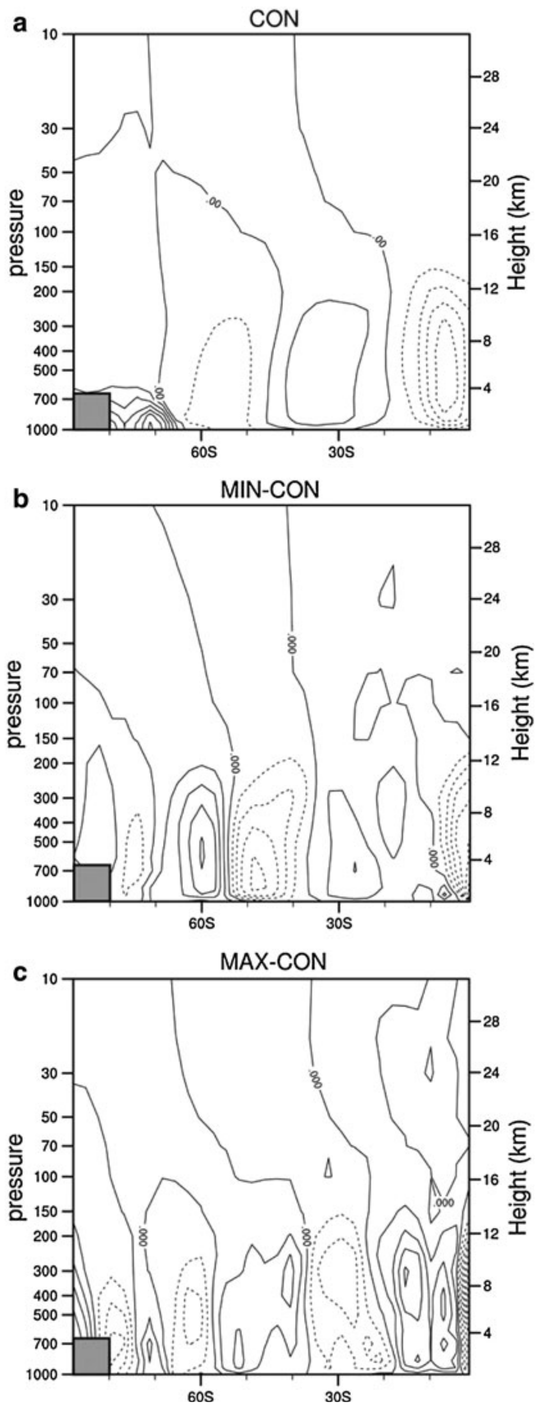

Fig. 10 Summer (JFM) hemispheric, zonally averaged vertical velocity (Omega). **a** Long term average CON and composite differences, **b** MIN–CON and **c** MAX–CON. Contour interval is 0.05 for **a** and 0.005 for **b** and **c**. Negative lines are *dashed*. Units are in centimeters per second

result in the composite differences that extend so deeply into the middle and upper troposphere. This large scale response to relatively small changes in SIC is possible because the sea ice lies in the sensitive region of the Antarctic polar frontal zone.

4 Sea ice and the SAM

The combined responses of the key variables discussed above—temperature, pressure and zonal wind—suggest that the average surface temperatures forced by the extreme sea ice distributions influence the state of the leading mode of variability in the Southern Hemisphere circulation, the SAM. The SAM is a mode of variability that is expressed in the geopotential height field as a see-saw in geopotential height between the polar regions and the middle latitudes. Lower geopotential heights over the poles coupled with higher heights over the midlatitudes constitute the positive polarity SAM. Based on the foregoing results the SAM appears to persist in negative polarity when there is less sea ice and positive polarity when there is more. This response is similar to those found by Marshall and Connolley (2006) when they modified the extra-tropical surface temperatures in winter. A reduced temperature gradient moved the SAM toward negative polarity. Additionally, observations suggest that there is a strong tendency for the SAM to exist in negative polarity in summer. (See Fig. 1 of Monaghan et al. 2008) likely due to the reduced temperature gradient which exists during that period.

Here we examine the SAM as represented in the atmospheric pressure field using the method described in Gong and Wang (1999). Figure 12 shows the summer SAM extracted from the three simulations. The index is calculated at 500 mb and normalized over the 120 years of the dataset. Note that the size and range of the index here is larger than observed. The information shown in Fig. 12 supports the earlier analysis and indicate that the SIC distribution can and does influence the polarity of the SAM. While there is short and long term variability apparent in all three indices, the overall responses differ remarkably. There is a strong and significant trend towards positive polarity in the MAX (MAX represents an unstable state), there is no trend in the CON (both polarities are represented with equal frequency) and the MIN, while also displaying no long term trend tends to be negative. A significant trend towards positive polarity in the SAM in the austral summer has been observed since the mid 1960s. This trend has been attributed to the combined effect of anthropogenic and natural forcings with the anthropogenic forcing being the more dominant of the two (Marshall et al. 2004). As designed, our experiments cannot address the role of these forcings on the SAM. However we note that sea ice concentration on average around Antarctica has experienced a slight but significant increase in recent decades (Cavalieri and Parkinson 2008). Sen Gupta and England (2006) show that sea ice concentration is indirectly affected by the SAM through the latter's impact on ocean, wind stresses and thermal effects. The results

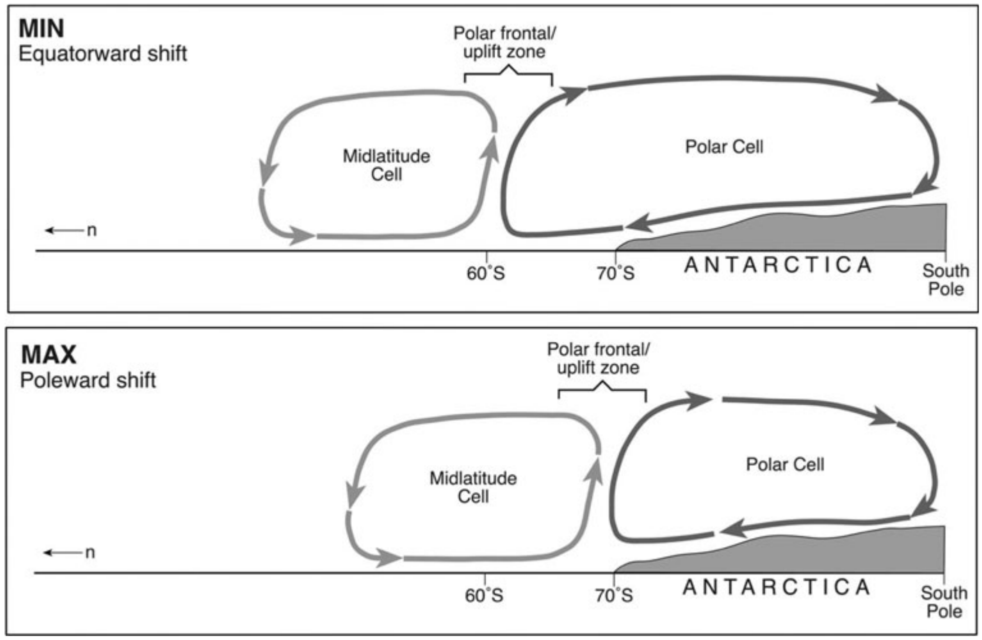

Fig. 11 Schematic of polar and midlatitude cell response to sea ice concentration

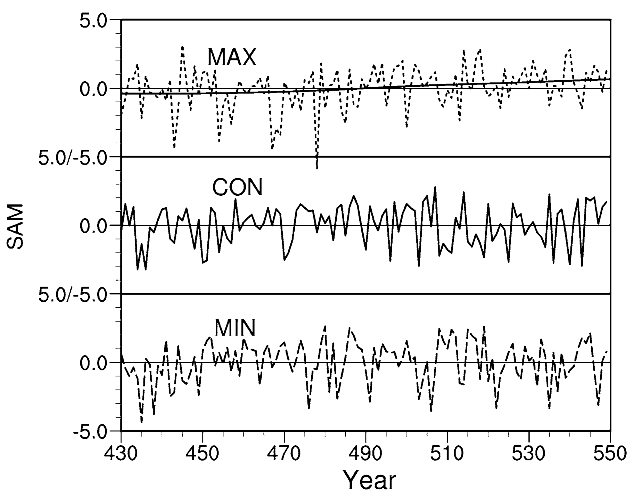

Fig. 12 Southern Hemisphere Annular Mode index at 500 hPa for MAX, CON, MIN

presented here suggest that the SIC in turn may have an impact on the SAM.

It could be argued that the variability seen in the simulations (Fig. 12) is internal to the system and not forced by the SIC. Some studies show that variability of the SAM may be due to internal atmospheric physics and may exist without external forcing. However, a number of studies suggest that it is sensitive to external forcing, especially its temporal evolution. Using ensemble AGCM integrations Zhou and Yu (2006) show that there is a small but significant predictability to the observed SAM when ocean SST is prescribed from observations.

Using regression analysis we removed the variability associated with the SAM from the SIC simulations above. The results show a slightly weaker pattern in the zonal wind (not shown) but the same sense as Fig. 12. Therefore the patterns that apparent in Fig. 12 are not forced solely by the natural variability of the SAM within the model. This reinforces the idea that sea ice has a significant impact on the whole atmosphere in the model.

Additionally, composite differences of the observed zonal circulation for the months that were used in creating the climatologies shows the same patterns as the simulated composite differences, especially for the MIN (Fig. 13). By inadvertently choosing sea ice distributions during a period when the SAM was in its negative mode (for the MIN) to force the model, we may have predisposed the SAM to occur in its negative polarity. However that only lends support to the idea that the SIC distributions reinforce the state of the SAM on interannual timescales.

5 Discussion and conclusions

We have used a fully coupled, global climate model, substituting its sea ice model with observed sea ice extremes, to examine the impact of Antarctic sea ice on the large scale, Southern Hemisphere atmosphere. Our results show that in summer, when sea ice is at its extreme minimum, the surface temperature and pressure in the circumAntarcic region are higher, the polar easterlies are stronger and they extend further north than average. In the midlatitudes, the surface temperature and pressure are generally lower, and the westerlies are weaker from 45°S to 60°S, but stronger from 30°S to 45°S. These responses extend into the upper atmosphere and occur in the opposite

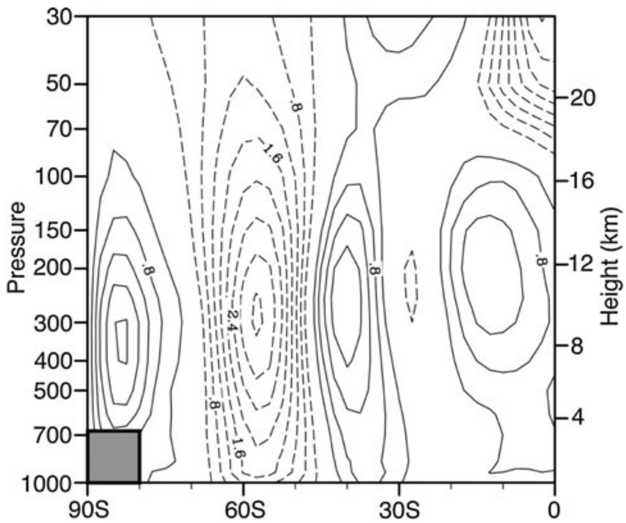

Fig. 13 Composite differences of observed zonal wind for the months used in creating the climatologies. Contour interval is 0.4. Units are in meters per second

sense when sea ice is at its extreme maximum. This combination of responses indicate that under minimum (maximum) sea ice extremes, there is an expansion (contraction) of the polar cell and subsequent equatorward (poleward) shift of the midlatitude (Ferrell) cell. We suggest that this is possible because the sea ice lies in the very sensitive margin between the polar and midlatitude cells, the subpolar frontal zone.

The influence of the SAM on sea ice has been explored to some extent. Lefebvre et al. (2004) show that the meridional winds associated with the non-annular component of the SAM create conditions that allow more ice to form in the Ross and Amundsen Seas and less ice to form in the Weddell Sea and around the Antarctic peninsula. Sen Gupta and England (2006) indicate that the effect that the SAM has on the ocean and on the atmosphere is transferred to sea ice dynamically and thermodynamically. Here we suggest that through its impact on temperature and pressure, sea ice also appears to influence the polarity of the Southern Hemisphere Annular Mode. When sea ice is at its minimum (maximum) the polarity of the SAM tends to be negative (positive). This result, while not previously explored, is tentatively supported by observations (Monaghan et al. 2008) and by the results of experiments done by Marshall and Connolley (2006).

The apparent influence of sea ice on the large scale circulation and on the SAM has relevance for our understanding of the current state of the Antarctic climate. Cavalieri and Parkinson (2008) report an identifiable average increase in sea ice over the past few years, obvious in summer in the Ross and Weddell seas and the western Pacific. The negative trend continues, but is reduced, in the Bellingshausen/Amundsen Seas. Steig et al. (2009) show that the continent of Antarctica is warming with significant warming over most of west Antarctica. Monaghan et al. (2008) found a widespread but not significant warming over Antarctica from 1992 to 2005 that coincided with a reduction of the positive trend in the SAM (positive polarity) during summer and autumn. Until recently (from the 1960s to 2006), the SAM exhibited a trend towards positive polarity. The significant positive trend of the SAM has been linked to increasing greenhouse gas concentrations (e.g. Cai et al. 2003; Rauthe et al. 2004) and to changes in stratospheric ozone (Thompson and Solomon 2002). Shindell and Schmidt (2004) and Arblaster and Meehl (2006) argue that both stratospheric ozone and increasing greenhouse gas concentration contribute to the trend while Marshall et al. (2004) argue that natural forcings have also played a role. Obviously, there are a number of factors influencing the large scale southern circulation and therefore, the state of the SAM. Our modeling study suggests that the state of the Antarctic sea ice, because of its influence on the surface temperature and its location at the margins of the Polar and Ferrell cells, is another very important contributor.

Currently a small but significant increase in Antarctic sea ice is observed. This increase is not simulated by our models; they simulate a decrease over the end of the twentieth century and over the whole of the twenty-first century (IPCC 2007). The consensus is that the current increase is associated with stratospheric ozone depletion (Turner et al. 2009) and our models which do not do an explicit treatment of the chemistry of the stratosphere are not able to replicate the increase. It is expected that Antarctic sea ice will decrease once the ozone recovery is complete. Within this context the response of the atmosphere to sea ice reported here has some significance. While we continue to observe an increase in SIC we may also see a contraction of the polar cell and the SAM may continue in its positive phase. If, as expected, stratospheric ozone recovers to normal levels, under present global warming trends the predicted reduction in SIC may lead to an expansion of the polar cell and a SAM that exists in negative polarity. In the absence of longer term records this highlights the need for coupled climate models with better representation of sea ice and sea ice/atmosphere interactions.

Acknowledgments This research is funded by the National Science Foundation ATM#0327268. Model runs were completed at the National Center for Atmospheric Research. Much of this work was undertaken whilst the authors were visiting the National Center for Atmospheric Research. We are grateful to Dr. Clara Deser for her helpful suggestions. We also thank two anonymous reviewers who made valuable comments and suggestions that improved the quality of the manuscript.

References

Arblaster JM, Meehl GA (2006) Contributions of external forcings to Southern Annular Mode trends. J Clim 19:2896–2905. doi:10.1175/JCLI3774.1

Bromwich DH, Chen B, Hines KM, Cullather RL (1998) Global atmospheric responses to Antarctic forcing. Ann Glaciol 27:521–527

Bryan FO, Kauffman BG, Large WG, Gent PR (1996) The NCAR CSM flux coupler. Technical Note, NCAR/TN-424+STR. National Center for Atmospheric Research, Boulder, CO

Cai W, Whetton PH, Karoly DJ (2003) The response of the Antarctic Oscillation to increasing and stabilized atmospheric CO_2. J Clim 16:1525–1538

Carleton AM (1981) Ice–ocean–atmosphere interactions at high southern latitudes in winter from satellite observation. Austral Meteorol Mag 29:183–195

Carleton AM (1988) Sea ice atmosphere signal of the Southern Oscillation in the Weddell Sea, Antarctica. J Clim 1:379–388

Cavalieri DJ, Parkinson CL (1981) Large-scale variations in observed Antarctic sea ice extent and associated atmospheric circulation. Mon Weather Rev 109:2323–2336

Cavalieri DJ, Parkinson CL (2008) Antarctic sea ice variability and trends, 1979–2006. J Geophys Res 113:C07004. doi:10.1029/2007JC004564

Cavalieri D, Parkinson CL, Gloersen P, Zwally HJ (1999) Deriving longterm time series of sea ice cover from satellite passive microwave multisensor datasets. J Geophys Res 104:803–815, 814

Collins WD, Bitz CM, Blackmon ML, Bonan GB, Bretherton CS, Carton JA, Chang P, Doney SC, Hack JJ, Henderson TB, Kiehl JT, Large WG, McKenna DS, Santer BD, Smith RD (2006) The community climate system model: CCSM3. J Clim 19:2122–2143. doi:10.1175/JCLI3761.1

Deser C, Walsh JE, Timlin MS (2000) Arctic sea ice variability in the context of recent wintertime atmospheric circulation trends. J Clim 13:617–633

Gong D, Wang S (1999) Definition of the Antarctic oscillation index. Geophys Res Lett 26:459–462

Hall A, Visbeck M (2002) Synchronous variability in the southern hemisphere atmosphere, sea ice, and ocean resulting from the annular mode. J Clim 15:3043–3057

Holland MM, Bitz CM, Hunke E (2005) Mechanisms forcing an Antarctic dipole in simulated sea ice and surface ocean conditions. J Clim 18:2052–2066

Hudson DA, Hewitson BC (2001) The atmospheric response to a reduction in summer Antarctic sea-ice extent. Clim Res 16:79–99

Intergovernmental Panel on Climate Change (IPCC) (2007) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change: the physical science basis, Cambridge University Press, New York

Kwok R, Comiso JC (2002) Southern ocean climate and sea ice anomalies associated with the Southern Oscillation. J Clim 15:487–501

Lefebvre W, Goosse H, Timermann R, Fichefet T (2004) Influence of the Southern Annular Mode on the sea-ice-ocean system. J Geophys Res 109:C09005. doi:10.1029/2004JC002403

Lemke P, Trinkl EW, Hasselmann K (1980) Stochastic dynamic analysis of polar sea ice variability. J Phys Oceanogr 10:2100–2120

Liu J, Curry JA, Martinson DG (2004) Interpretation of recent Antarctic sea ice variability. Geophys Res Lett 31:L02205. doi:10.1029/2003GL018732

Marshall GJ, Connolley WM (2006) Effect of changing Southern Hemisphere winter sea surface temperatures on Southern Annular Mode strength. Geophys Res Lett 33:L17717. doi:10.1029/2006GL026627

Marshall GJ, Stott PA, Turner J, Connolley WM, King JC, Lachlan-Cope TA (2004) Causes of exceptional atmospheric circulation changes in the Southern Hemisphere. Geophys Res Lett 31(14):L14205. doi:10.1029/2004GL019952

Maykut GA (1986) The surface heat and mass balance. In: Untersteiner N (ed) The geophysics of sea ice. Plenum Press, NY, pp 489–549

Mitchell JFB, Senior CA (1989) The Antarctic winter; simulations with climatological and reduced sea-ice extents. Q J R Meteorol Soc 115:225–246

Monaghan AH, Fyfe JC (2006) On the nature of zonal jets. J Clim 19:6409–6424. doi:10.1175/JCLI3960.1

Monaghan AJ, Bromwich DH, Chapman W, Comiso JC (2008) Recent variability and trends of Antarctic near-surface temperature. J Geophys Res 113:D04105. doi:10.1029/2007JD009094

Raphael M (2002) Response of the large-scale Southern Hemisphere extra-tropical circulation to extremes of Antarctic sea ice concentration in a general circulation model. Polar Geogr 25:218–238

Raphael MN (2003) Impact of observed sea-ice concentration on the Southern Hemisphere extratropical atmospheric circulation in summer. J Geophys Res 108:4687. doi:10.1029/2002JD003308

Raphael MN (2007) The influence of atmospheric zonal wave three on Antarctic sea ice variability. J Geophys Res 112(D12): D12112. doi:10.1029/2006JD007852

Raphael MN, Holland MM (2006) Twentieth century simulation of the southern hemisphere climate in coupled models. Part I: large scale circulation variability. Clim Dyn 26:217–228. doi:10.1007/s00382-005-0082-8

Rauthe M, Hense A, Paeth H (2004) A model intercomparison study of climate change signals in extratropical circulation. Int J Climatol 24:643–662

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J Geophys Res 108:4407. doi:10.1029.2002JD002670

Sen Gupta A, England M (2006) Coupled ocean–atmosphere–ice response to variations in the Southern Annular Mode. J Clim 19(18):4457–4486

Shindell DT, Schmidt GA (2004) Southern Hemisphere climate response to ozone changes and greenhouse gas increases. Geophys Res Lett 31:L18209. doi:10.1029/2004GL020724

Simmonds I, Budd WF (1991) Sensitivity of the Southern Hemisphere circulation to leads in the Antarctic pack ice. Q J R Meteorol Soc 117:1003–1024

Simmonds I, Jacka TH (1995) Relationships between the interannual variability of Antarctic sea ice and the Southern Oscillation. J Clim 8:637–647

Simmonds I, Wu X (1993) Cyclone behaviour response to changes in the winter Southern Hemisphere sea-ice concentration. Q J R Meteorol Soc 119:1121–1148

Stammerjohn SE, Martinson DG, Smith RC, Yuan X, Rind D (2008) Trends in Antarctic annual sea ice retreat and advance and their relation to ENSO and Southern Annular Mode Variability. J Geophys Res 113:C03S90. doi:10.1029/2007JC004269

Steig EJ, Schneider DP, Rutherford SD, Mann ME, Comiso JC, Shindell DT (2009) Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. Nature 457:459–463

Thompson DWJ, Solomon S (2002) Interpretation of recent Southern Hemisphere climate change. Science 296:895–899

Turner J, Comiso JC, Marshall GJ, Lachlan-Cope TA, Bracegirdle T, Maksym T, Meredith MP, Wang Z, Orr A (2009) Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. Geophys Res Lett. doi:10.1029/2009GL037524

Walsh JE (1993) Observational and modelling studies of the influence of sea-ice anomalies on atmospheric circulation. In: Shukla J (ed) NATO ASI series. Prediction of interannual climate variations, vol 6. Springer, Berlin

Yuan XJ, Li CH (2008) Climate modes in southern high latitudes and their impacts on Antarctic sea ice. J Geophys Res Oceans 113:C06S91. doi:10.1029/2006JC004067

Yuan X, Martinson DG (2001) The Antarctic Dipole and its predictability. Geophys Res Lett 28:3609–3612

Zhang J (2007) Increasing Antarctic sea ice under warming atmospheric and oceanic conditions. J Clim 20:2515–2529

Zhou T, Yu R (2006) Twentieth century surface air temperature over China and the globe simulated by coupled climate models. J Clim 19:5843–5858