IMPACT OF REDUCED SEA ICE CONCENTRATION ON THE ANTARCTIC MASS BALANCE

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1. INTRODUCTION

The study of climate in polar regions is complicated by the existence of sea ice. Associated with this it has been suggested that the polar regions may undergo greater Greenhouse Effect changes than would be experienced elsewhere, because of the albedo-temperature effects of the sea ice. These perturbations to the polar environments are of relevance to the International Geosphere Biosphere Program because they will have an impact on the climate of the whole globe. The changes in the Southern Hemisphere (SH) may be particularly marked because of the very dynamic nature of Antarctic sea ice being, as it is, located at lower latitudes and less confined by the continents than its northern counterpart. The potential severity of some of these effects behooves us to increase our understanding of the interaction of the various processes.

It is now well appreciated that the presence of sea ice dramatically changes the fluxes of heat and momentum across the air-surface interface. The albedo and roughness of a sea ice cover differ so greatly from those over open water that the above fluxes can differ by orders of magnitude or even have opposite signs.

Modern remote sensing techniques have enabled us to obtain a comprehensive picture of the spatial and temporal distribution of sea ice over the globe (e.g., Zwally *et al.* [1], Parkinson *et al.* [2] and Gloersen & Campbell [3]). The findings of these studies make it clear that polar sea ice cannot be thought as a continuous slab but has within it large areas of open water (or 'leads'). It follows from what was said above that even rather small regions of open water are able to significantly affect the fluxes of heat across the surface-atmosphere boundary (e.g., Andreas & Murphy [4]) and hence the *concentration* of sea ice in the polar regions is a parameter of considerable importance.

2. FORMAT OF THIS STUDY

As implied above, if the global climate is changing we may see the first regional manifestations at high latitudes. Two of the parameters which may be affected are the ice extent in the two hemispheres and the concentration within the sea ice boundaries. Using nine years of Nimbus 7 scanning multichannel microwave radiometer data [3] found significant negative trends in the annual global ice extent maxima and in the annual open water maxima in the Antarctic sea ice. Hence, for whatever reason, some aspects of the distribution and concentration of polar sea ice have undergone trends in the last decade.

With these changes in mind, our aim in this study is to estimate the effect of changes in Antarctic sea ice concentration, particularly with a view to the response of surface evaporation and precipitation over the sea ice zone and Antarctica. Due to the complex nature of the sensitivities of climate at high latitudes we believe a very fruitful approach is to perform these studies with the aid of a General Circulation Model (GCM). The basic structure and performance of the model we use in the present set of experiments is given in Simmonds [5] and Simmonds *et al.* [6]. In the model the sea ice distribution and thickness is specified and not permitted to change. However, it does incorporate the effect of leads in the sea ice zones in the manner discussed by Simmonds & Budd [7]. (In the sea ice zones each 'grid box' is conceived to be broken into a sea ice part and an open leads part. The fraction of open water in the ice pack (f_w) is, for simplicity, not considered to vary with position but is prescribed as different values in the two hemispheres. For a given atmospheric structure, the surface fluxes are very different over the two sub-domains. To account for the strong nonlinear effects the scheme performs separate flux calculations over the sea ice and open water parts of the box. The surface temperature over the open water part is specified as the freezing point of sea water, 271.4K. These fluxes are then averaged with the appropriate area weighting and the transports communicated to the lowest level of the model.)

The studies reported here were conducted with the 'perpetual July' 21 wave, 9 level version of the model. Results are shown here of four experiments in each of which f_w in the Northern Hemisphere is set to 0.05; i.e., 5% open water. In the SH sea ice the values were prescribed as 0.05, 0.50, 0.80 and 1.00, and these simulations are denoted as I, II, III and IV, respectively. (Note that IV is equivalent to the complete removal of SH sea ice.) The 'control' simulation of the GCM, with which these experiments are compared, was run with no leads in either hemisphere (i.e., $f_w = 0.0$) and its climate is estimated from a 600-day period run. (The climatology of this control is shown, and compared with observations, in [6].) The climates of the anomaly runs were derived from the analysis of 300-day simulations, after an adjustment period of 90 days.

3. RESULTS

The allowance for open leads in the Antarctic ice pack has the immediate effect of increasing the temperature and moisture availability of the surface. As a result of this there are large anomalies of upward sensible and latent surface heat fluxes in the sea ice zone, which in turn have an impact on the large-scale circulation. The latent heat flux changes, while not as dramatic as those of sensible heat, are large and it is their impact on the moisture balance at high latitudes that interests us here.

Figure 1 displays the change in evaporation rate from the control case over the high southern latitudes. (Parts (a) through (d) of the Figure display the changes in experiments I, II, III and IV, respectively.) In experiment I (5% open water in the sea ice) there is an increase in evaporation almost everywhere over the area of sea ice, but these increases are everywhere less than 0.5 mm day^{-1}. (The sea ice distribution prescribed in the model is not shown explicitly here but its northern limit corresponds with the contour of zero

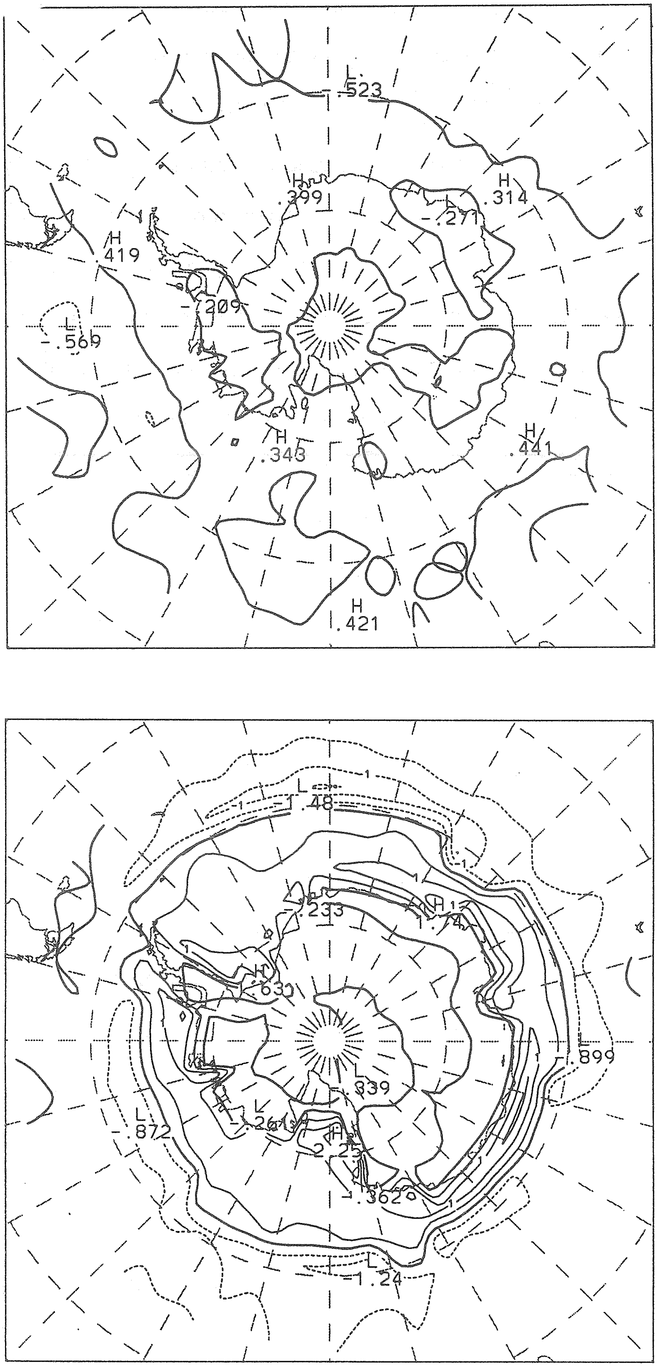


Fig. 1. Difference between the evaporation of the I (a) (top), and II (b) (bottom) and the control simulations. The contour interval is 0.5 mm day^{-1}, the zero contour is accentuated and negative contours are dashed.

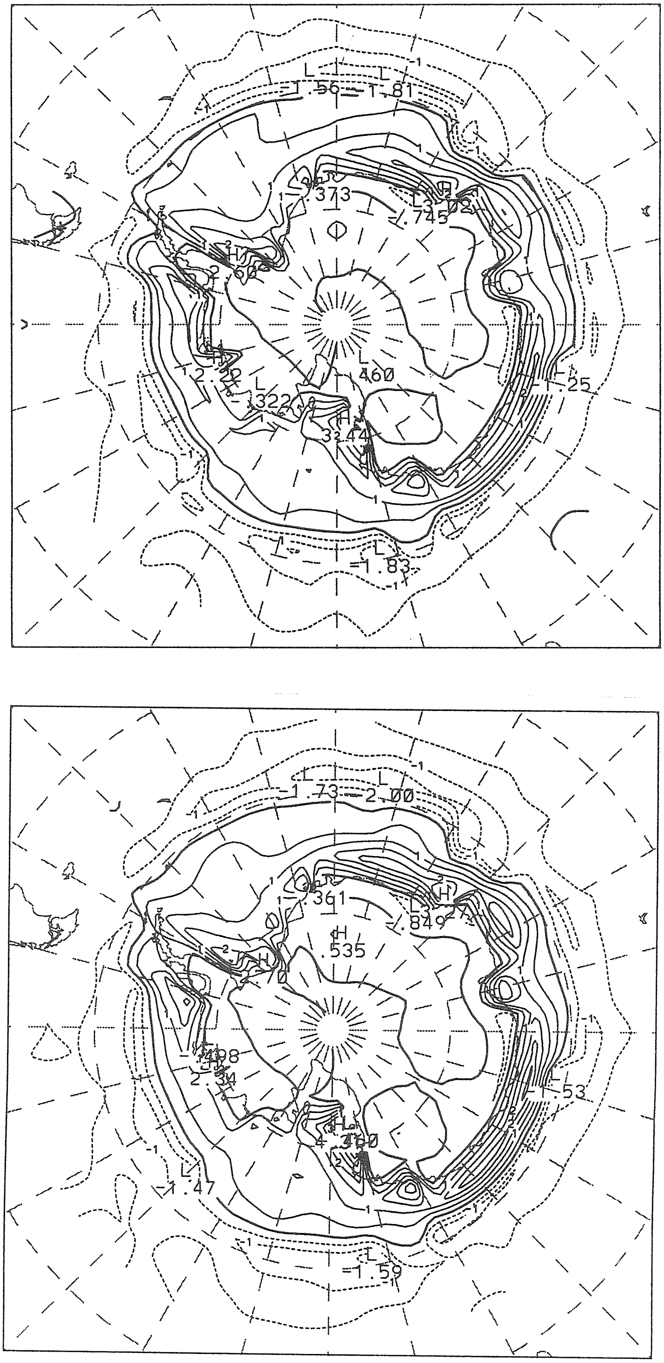
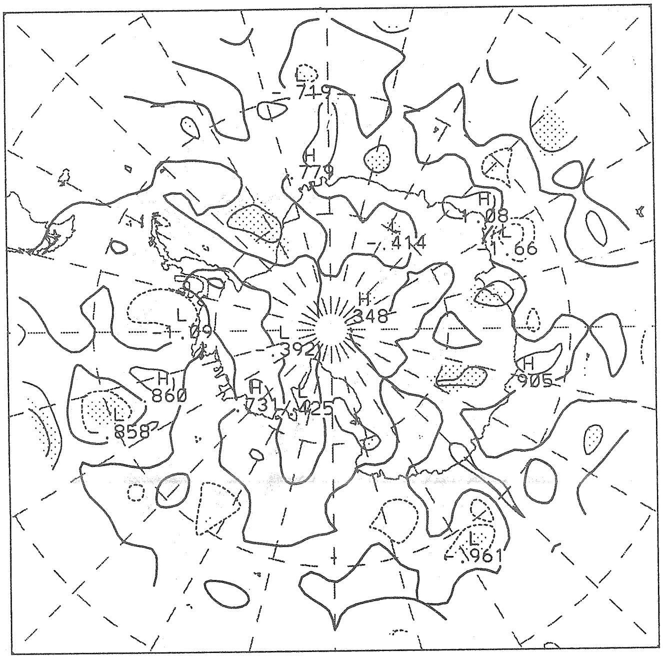


Fig. 1. Difference between the evaporation of the III (c) (top), and IV (d) (bottom) and the control simulations. The contour interval is 0.5 mm day^{-1}, the zero contour is accentuated and negative contours are dashed.



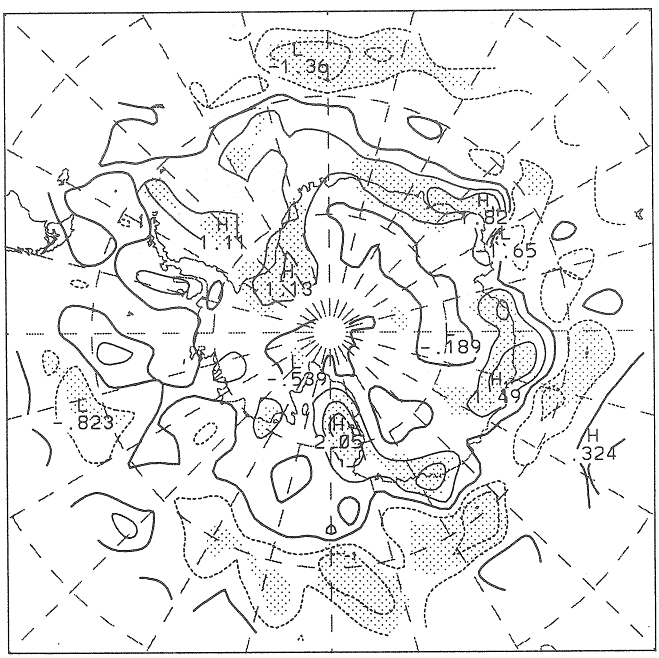


Fig. 2. Difference between the precipitation of the I (a) (top), and II (b) (bottom) and the control simulations. The contour interval is 0.5 mm day^{-1}, the zero contour is accentuated and negative contours are dashed. Regions of differences significant at the 95% confidence level are stippled.

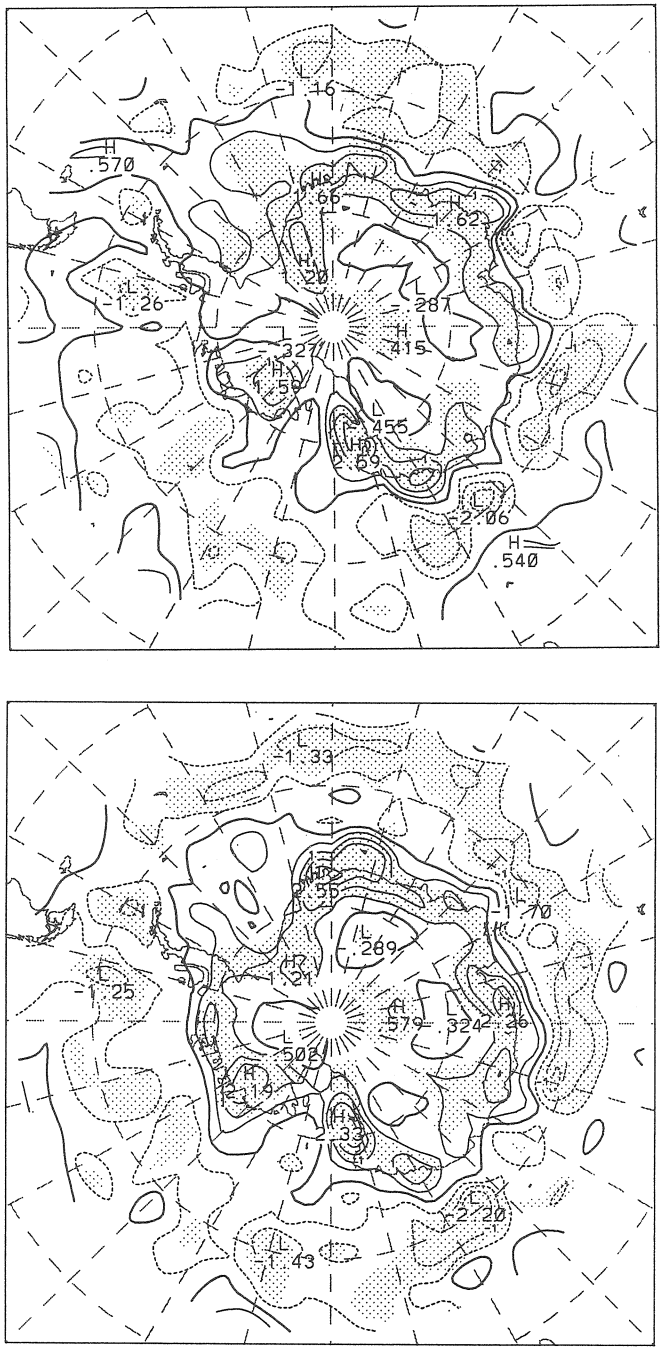


Fig. 2. Difference between the precipitation of the III (c) (top), and IV (d) (bottom) and the control simulations. The contour interval is 0.5 mm day^{-1}, the zero contour is accentuated and negative contours are dashed. Regions of differences significant at the 95% confidence level are stippled.

evaporation change displayed clearly in, e.g., part (b) of the Figure.) The pattern of evaporation change in II (Figure 1(b)) is more clear-cut. Again, the evaporation has increased over the sea ice region, by in excess of 0.5 mm day^{-1} at most locations and by more than 2 mm day^{-1} in the western Ross Sea. The pattern of the changes are similar in III and IV (Figures 1(c) and (d)) but, not surprisingly, the magnitude of the changes are greater. A common response in these experiments is that while the evaporation increases over the sea ice area, there are decreases to the north in all cases. This is consistent with the findings of Simmonds [8] and Mitchell & Senior [9]. The juxtaposition of these positive and negative anomalies is presumably due to the fact that low level air flowing off the continent picks up more moisture as it flows over the ice with leads than it would over solid ice. Hence such air reaches the open ocean moister and the upward flux of latent heat there is considerably reduced.

The changes in precipitation rate induced in the four experiments are displayed in a similar fashion in Figure 2. (In this Figure stippled areas are those over which the changes are significant at the 95 per cent confidence level.) The precipitation changes tend to be much less organized than those of evaporation which is not surprising as moisture evaporated from the surface (or advected from elsewhere) is subjected to turbulent atmospheric motions before it is deposited in some (possibly non-local) region. From Figure 2 (a) we can see that very few of the changes in the I experiment achieve statistical significance. As f_w is increased a clearer pattern of change emerges with the differences becoming larger and more significant (Figure 2 (b)-(d)). In certain regions there is almost a local balance between evaporation and precipitation, while in most regions this is far from being so. Indeed in some locations, e.g., in the Amundsen Sea in III, there is increased evaporation but *reduced* precipitation. In experiments II, III and IV there is clear evidence for more precipitation over much of coastal Antarctica and the southern part of the sea ice. Further to the north and out over the open sea these three experiments reveal a reduction in precipitation rate associated with the ice leads. It is not apparent that there is any consistent change over the sea ice region as a whole in the experiments, despite the fact that the evaporation increases there.

4. DISCUSSION AND CONCLUDING REMARKS

A convenient way of summarising the changes in the moisture budget over the sea ice and the Antarctic continent is to calculate the mean evaporation and precipitation over these regions. This is information is presented in Table 1, along with the averages obtained in the control simulation.

Experiment	Evaporation over sea ice	Precipitation over sea ice	Evaporation over Antarctica	Precipitation over Antarctica
Control(C)	0.71	2.47	0.56	1.02
I-C	0.13	0.00	0.01	0.07
II-C	0.80	0.15	-0.03	0.28
III-C	1.01	-0.05	-0.06	0.35
IV-C	0.98	-0.06	-0.05	0.48

Table 1. Average values (area-weighted) of evaporation and precipitation over the Antarctic sea ice and the Antarctic continent. I, II, III and IV refer to the experiments with Antarctic sea ice water fractions of 5, 50, 80 and 100%, respectively. The units are mm day^{-1}.

As expected, the evaporation over the Antarctic sea ice is always greater when leads are considered and it depends virtually monotonically on f_w. There is also a considerable degree of nonlinearity in that small open water fractions can give rise to proportionally large evaporation changes. For example, a leads fraction of only 5% results in 13% of the change that complete ice removal produces. In a similar vein, $f_w = 0.50$ is associated with 82% of that change. The second column in Table 1 supports the impression gained from the maps that there appears to be little or no consistent change in precipitation over the sea ice as a whole. One then asks what is the fate of most of the moisture which is evaporated over the sea ice? The last two columns of Table 1 indicate that a portion of it is deposited over the Antarctic ice mass. It is seen that the changes in evaporation from the Antarctic surface are very small, but that the precipitation rate increases are monotonically related to f_w. Most of this precipitation which falls on the continent is frozen and lost to the oceanic water balance, contributing to a lowering of global sea level.

A typical value of f_w for the winter Antarctic sea ice is 0.20. We estimate from the Table that for this concentration the precipitation over the continent would increase by 0.16 mm day^{-1}, which implies an Antarctic precipitation change of 10% as f_w is increased from 0.20 to 0.50. The model overestimates the winter Antarctic precipitation but to gain an estimate of how the real climate system would respond to $f_w = 0.50$ we have applied this percentage increase to the actual annual precipitation rate (about 150 mm year^{-1}). However, before we can estimate the annual response implied by percentage increase in our July simulation we need to allow for the fact that the effect of leads is obviously less when the area of sea ice cover is small. To allow for this in a crude way we have multiplied the July percentage precipitation increase by the ratio of the annual average Antarctic sea ice area (11 x 10^6 km^2) and the July area (16 x 10^6 km^2), a factor of 0.7. This implies an increase of 10.5 mm year^{-1} over the continent. Dividing this by a factor of 26, the ratio of the area of the world's oceans to that of Antarctica, results in a sea level lowering of 0.40 mm year^{-1}. Similar analyses applied to III and IV as measured against the 20% open water case produces model percentage precipitation increases of 16 and 27%, respectively. Following reasoning similar to above these applied to the actual precipitation would result in sea level drops of 0.65 and 1.09 mm year^{-1}.

This study has revealed aspects of the non-local nature of the atmospheric hydrologic cycle. The opening up of open water in the sea ice zone certainly increases evaporation but, by and large, this anomalous moisture is precipitated out remotely. This emphasises the dangers inherent in trying to understand the anomalous water budget in purely local terms and points out the central role played by the atmospheric circulation. The situation is further complicated by the fact that the circulation is, in itself, affected by the changes in open water fraction. It is clear that a large scale and comprehensive perspective must be maintained if we are to obtain an adequate understanding of changes which may affect the Antarctic mass balance in the coming decades. We should reiterate that in our experiments the sea ice distributions and concentrations are fixed and not allowed to change. In reality it is possible that some of the feedback mechanisms operating would attempt to alter both of these. Also, here we have been concerned with the response to changes that may occur in Antarctic sea ice concentration under global warming conditions. We have not considered here the effect on precipitation of the warming of the waters to the north of the continent, which could be thought of as giving an impact of the same sign as those considered here. Results of experiments of this impact will be published elsewhere.

REFERENCES

[1] ZWALLY, H.J., COMISO, J.C., PARKINSON, C.L., CAMPBELL, W.J., CARSEY, F.D. and GLOERSEN, P., (1983) Antarctic sea ice, 1973-1976: Satellite passive-microwave observations. *NASA Scientific and Technical Information Branch, NASA SP-459,* 206pp.

[2] PARKINSON, C.L., COMISO, J.C., ZWALLY, H.J., CAVALIERI, D.J., GLOERSEN, P. and CAMPBELL, W.J., (1987) Arctic sea ice, 1973-1976: Satellite

passive-microwave observations. *NASA Scientific and Technical Information Branch, NASA SP-489*, 296pp.

[3] GLOERSEN, P. and CAMPBELL, W.J., (1988) Variations in the Arctic, Antarctic, and global sea ice covers during 1978-1987 as observed with the Nimbus 7 scanning multichannel microwave radiometer. *J. Geophys. Res.* **93**, 10666-10674.

[4] ANDREAS, E.L. and MURPHY, B., (1986) Bulk transfer coefficients for heat and momentum over leads and polynyas. *J. Phys. Oceanogr.* **16**, 1875-1883.

[5] SIMMONDS, I., (1985) Analysis of the 'spinup' of a general circulation model. *J. Geophys. Res.* **90**, 5637-5660.

[6] SIMMONDS, I., TRIGG, G., and LAW, R., (1988) The Climatology of the Melbourne University General Circulation Model. *Publication No. 31, Department of Meteorology, University of Melbourne* [NTIS PB 88 227491], 67pp.

[7] SIMMONDS, I., and BUDD, W.F., (1990) A simple parameterization of ice leads in a GCM and the sensitivity of climate to a change in Antarctic ice concentration. *Annals of Glaciology* **13**, (in press).

[8] SIMMONDS, I., (1981) The effect of sea ice on a general circulation model of the Southern Hemisphere. *Sea Level, Ice, and Climate Change Proceedings of the IUGG Canberra Symposium, December 1979. IAHS Publ. no. 131*, 193-206.

[9] MITCHELL, J.F.B. and SENIOR, C.A., (1989) The Antarctic winter: simulations with climatological and reduced sea-ice extents. *Quart. J. Roy. Meteor. Soc.* **115**, 225-246.

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