Tellus (1998), 50A, 424–441
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TELLUS
ISSN 0280–6495

Sensitivity of the Southern Hemisphere Semiannual Oscillation in surface pressure to changes in surface boundary conditions

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(Manuscript received 10 September 1997; in final form 2 February 1998)

ABSTRACT

The Melbourne University General Circulation Model has been used to simulate the climate of the Southern Hemisphere and its portrayal of the Semiannual Oscillation (SAO) in surface pressure has been assessed. The model is shown to underestimate the amplitude of the SAO slightly but simulate its general structure quite well. To assess the relative importance of various factors in determining the characteristics of the SAO, we perform several anomaly experiments. In particular, we conduct an experiment where the Antarctic topography is leveled, an experiment where the sea ice surrounding the Antarctic continent is removed and also an experiment that combines the two changes. The impact on the SAO is examined as a means to attempt to determine what the mechanisms for the changes are. The removal of topography, in particular, is demonstrated to have a great effect on the SAO, while the sea ice makes a more modest impact but of the opposite nature. Some possible mechanisms are suggested.

1. Introduction

The surface pressure in the middle to high latitudes of the Southern Hemisphere exhibits a strong half yearly wave, commonly referred to as the Semi-annual Oscillation (SAO). The amplitude of this half yearly wave often exceeds that of the annual cycle in many places. The phenomenon has been discussed extensively in the literature (Van Loon 1967, 1972; Hsu and Wallace 1976; Streten 1980; van Loon and Rogers 1984; Meehl 1991; Hurrell and Van Loon 1994; Simmonds and Jones 1998). The oscillation is understood to derive from the dynamic effect of the differing annual variations in tropospheric temperatures in the oceanic and Antarctic southern latitudes. Whereas over the Antarctic the sun disappears early in the year and the temperatures start to drop, over the ocean this happens later. Similar tendancies occur at the end of the year. The rates of warming and cooling between the two annual cycles of temperature also vary due to the complex energy balance over the ocean and the landmass. This all leads to meridional temperature gradients in the middle troposphere between approximately 50°S and the Antarctic continent that exhibit a significant half yearly wave. The temperature gradients and the associated baroclinicity lead to an SAO in surface pressure through this region. Meehl (1991) found that there was a marked SAO in the transient eddies at 850 and 300 hPa. Support for this observation was given by independent analyses of transient activity by Trenberth (1991) and Jones (1994). The circumpolar trough was demonstrated to move south and intensify during

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the equinox periods (as proposed by van Loon 1967) and there was an associated maximum in the eddy momentum. Several authors (Carleton 1981; Howarth 1983; Jones 1994) have suggested a link between the semiannual baroclinic activity and the annual cycle of eddy activity.

Many of the earlier studies have been of an observational nature. There have also been some investigations that have utilised General Circulation Models (GCMs) to simulate the annual cycle of surface pressure and highlight a SAO signal in the mid to high southern latitudes (Weickmann and Chervin, 1988; Xu et al., 1990; Kitoh et al., 1990; Meehl, 1991, Mullan and McAvaney, 1995; Simmonds and Walland, 1998). These models have shown varying degrees of success in their representation of the phenomenon. Mullan and McAvaney (1995) survey the output from AMIP simulations and show a wide variation in model ability at simulating the SAO.

That the SAO dominates the long term sea level pressure over large regions south of the subtropical ridge does not mean that it is necessarily always the strongest signal. Hurrell and van Loon (1994) show from long term station records that the phase of the semiannual wave is very stable compared with that for the annual wave for instance and thus in the long term mean it dominates. van Loon and Rogers (1984) show that the SAO is present in unfiltered data for individual years but document significant interannual variability. There is now evidence of variability on interannual to decadal time scales (Van Loon et al., 1993; Hurrell and van Loon, 1994; Simmonds and Jones, 1998). The relatively short nature of the observational record, however, limits the confidence that we can have in such results. Is the current shift to a period of very low SAO abnormal or is it perhaps more the norm and the previous period with which we had to compare it to abnormally high? These are questions that cannot be answered with the current relatively short historical record. Simmonds and Walland (1998) show using a simulation from the GFDL coupled model that such variability seen in the last few decades could be well within the realms of natural variability. However these are model results and as such must be treated with caution. In addition there has been very little work done with aim of exploring the mechanisms that might be responsible for such variability. It is this that we are attempting in the present study.

Two of the most distinctive characteristics of the high southern latitudes are the presence of the elevated Antarctic topography and extensive sea ice (and its large seasonal variation). There are many physical reasons for believing that these features significantly impact on the pressure distributions and in particular the SAO, in the Southern Hemisphere. Our aim in this study is to assess the ability of a numerical model, the Melbourne University General Circulation Model (MUGCM) to simulate the SAO. We also want to document the sensitivity of its simulated structure to the removal of Antarctic topography and of the sea ice. In an attempt to understand how these boundary conditions are affecting the climate system, we examine the differences in various fields including surface pressure and also importantly, temperature and the meridional temperature gradient throughout the atmosphere between the model control simulation and the sensitivity experiments.

2. Model and its simulation of the annual and semiannual cycles

The MUGCM is a spectral model with the spherical harmonic series rhomboidally truncated at wave number 21. This corresponds to a horizontal resolution of approximately $5.6^\circ \times 3.3^\circ$. The model uses nine vertical sigma levels. It uses the Fels and Schwarzkopf (1975) radiation formulation which includes a diurnal cycle and also an interactive cloud formulation (Argete, 1993; Argete and Simmonds, 1996). The GCM is discussed in Simmonds (1985), Simmonds and Lynch (1992) and Simmonds and Law (1995). In the model, sea surface temperatures (SSTs) are prescribed based on the climatology of Reynolds (1988).

The control simulation of the model has been run in seasonal mode for 20 years. Our first aim is to assess the accuracy to which the model represents the SAO. This is of interest in its own right and also allows us to determine the confidence we would have in the sensitivity of the modelled SAO to changes in boundary conditions. Firstly we present a time series of surface pressure from the model at a latitude (zonal average) where the SAO is known to be significant in the observations. The work of Simmonds and Jones (1998) suggests that observations exhibit a reasonably strong second harmonic around latitude 68°S. The time series is given in Fig 1a. A harmonic analysis of this time series reveals the power spectrum for each frequency band. This is given in Fig. 1b. The power spectrum indicates a clear peak for variability with a period of 6 months. There are other peaks in the spectrum but this is certainly the strongest and of interest; it is a good deal stronger than the annual cycle (period of 12 months). Thus the model appears to be picking out the dominance of the second harmonic in surface pressure at these latitudes.

In Fig. 2 we present the amplitudes and variance explained for the second harmonic of the annual cycle of surface pressure in the control. For each month, we have averaged all data over the integration and to this time series we have applied a harmonic analysis and extracted out for the second harmonic, the amplitude and variance explained by this harmonic. For comparison purposes we present observations of the same parameters (Fig. 3) calculated from the mean of 21 years (1973–1993) of the Australian Southern Hemispheric analyses. The model has simulated

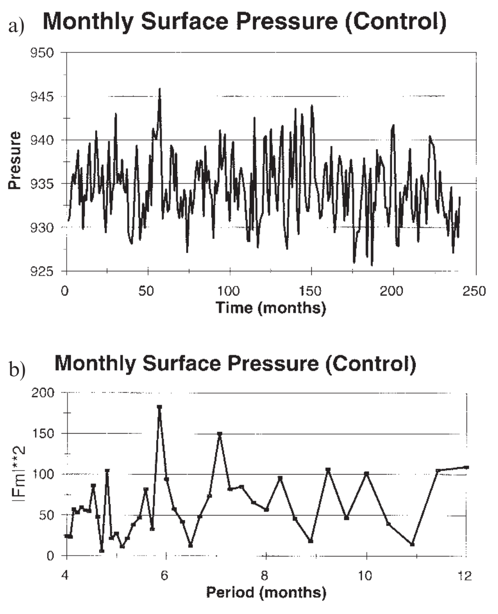


Fig. 1. (a) Zonal average surface pressure (hPa) at latitude 68°S based on calendar month averages from 20 year MUGCM control run. (b) Power spectrum of the time series of surface pressure in (a).

some of the basic features of the SAO although the amplitudes do look a little weak. In comparison with simulations from other models (Mullan and McAvaney 1995) the MUGCM appears to do quite well. The simulation does have some problems in the South Atlantic but its quality is very good in the western Pacific Ocean and the Indian Ocean in particular. The South Atlantic shows a region of minima off the coast and maxima equatorward of this but the pattern would appear to be somewhat equatorward of that depicted in the observations. The Indian Ocean shows fairly zonal structure with a belt of minima around 55°S equatorward of the maximum amplitudes over the Antarctic continent just as is seen in the observations. The amplitudes are not as consistently high over the continent but this was found to be a manifestation of our use of surface pressure rather than the mean sea level pressure displayed in Fig. 3. We prefer to use surface pressure for the model rather than mean sea level pressure as the latter incorporates the uncertainties associated with the interpolation of the pressure (using an assumed temperature profile) through the Antarctic landmass down to sea level. Further equatorward, in the Indian Ocean is another region where SAO activity is at a maximum as depicted in the observed data. In the South Pacific, the pattern is not nearly so zonal. As the observations show, in the western South Pacific, the maximum in the SAO extends much further equatorward than in the east. This is accurately simulated by the model.

The variance explained in the control simulation (Fig. 2b) also approximates that for the observations (Fig. 3b). Maxima are also largely over the Antarctic continent, particularly near the coast. The Indian Ocean shows the minimum in variance equatorward of this but does not have the pronounced maxima at around 30–50°S that the observations show. The model does, however, simulate the SAO quite well in the South Atlantic and Pacific. The maxima in the western South Atlantic is well captured. The meridional structure across the Pacific is also seen with a corresponding minima in variance explained by the second harmonic north of the Bellingshausen Sea and then a maxima southeast of New Zealand.

The model also shows skill in simulating the amplitude of the first harmonic of surface pressure. We compare it (Fig. 4) with that revealed in the

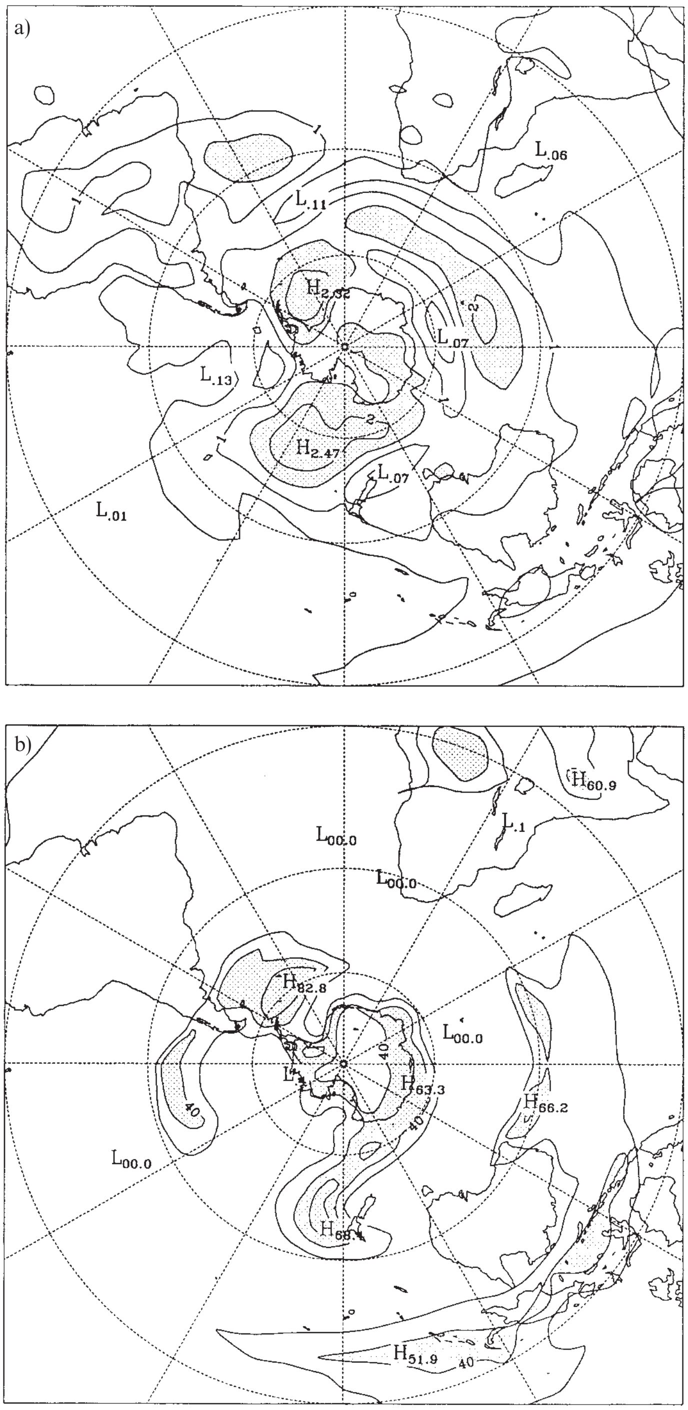


Fig. 2. Spatial distribution of (a) amplitude (hPa) and (b) variance explained (%) for the second harmonic of surface pressure based on calendar month averages from 20 year MUGCM control run.

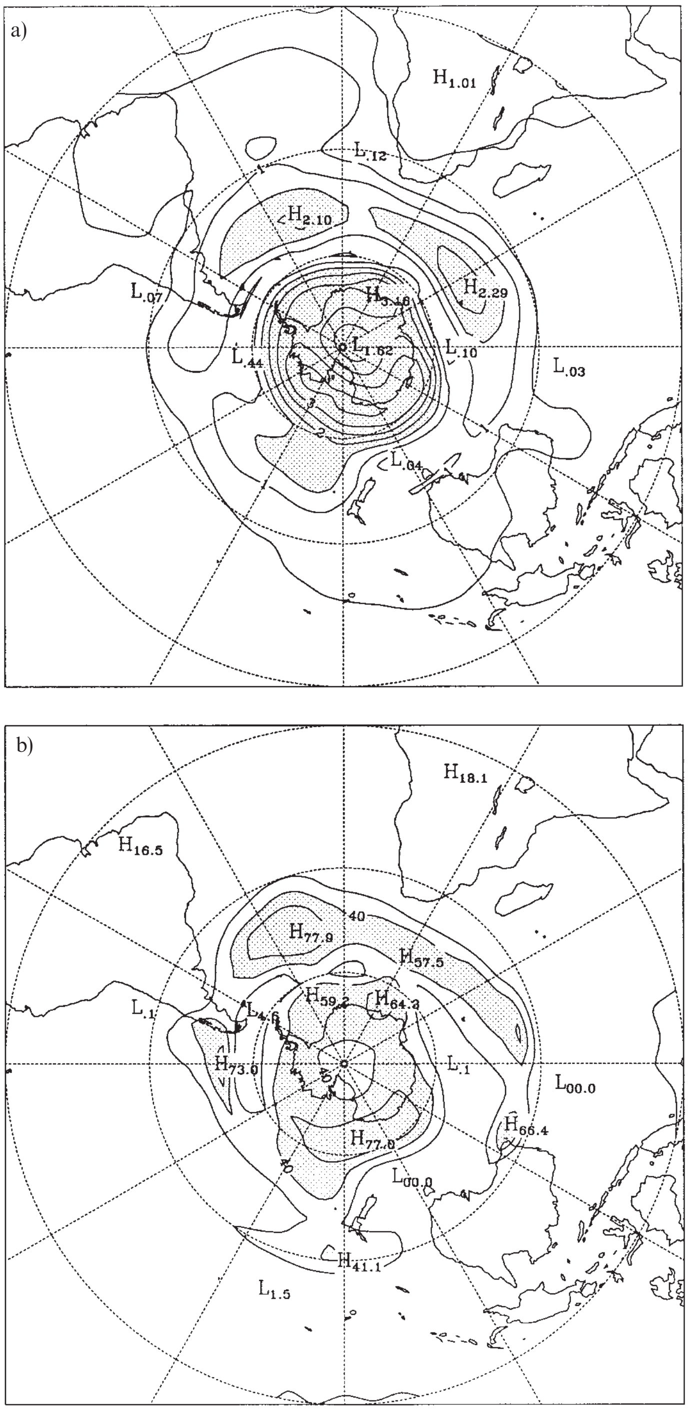


Fig. 3. Spatial distribution of (a) amplitude (hPa) and (b) variance explained (%) for the second harmonic of surface pressure based on calendar month averages from 21 years (1973–1993) of Southern Hemispheric analyses.

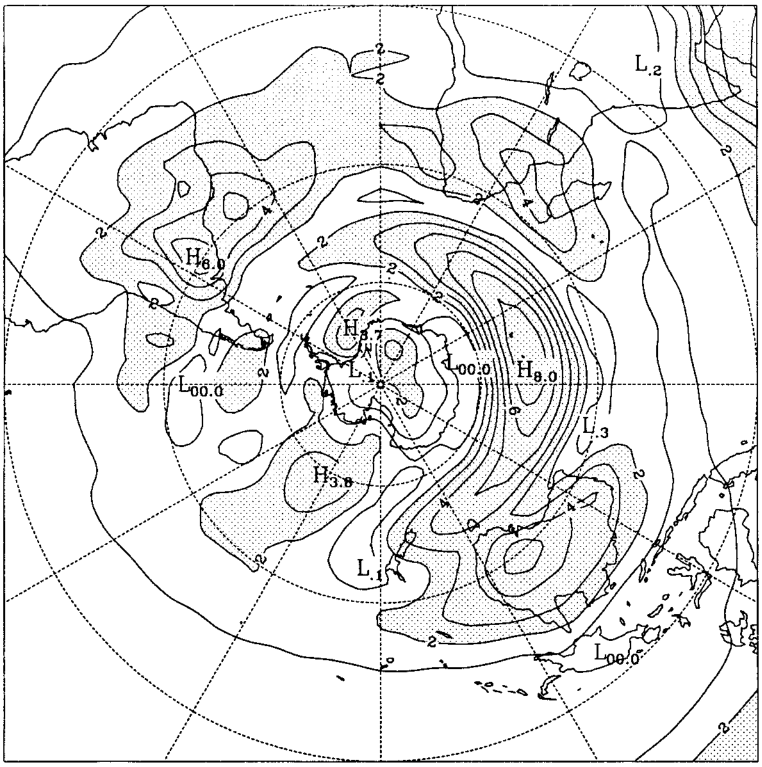


Fig. 4. Spatial distribution of amplitude (hPa) for the first harmonic of surface pressure based on calendar month averages from 20 year MUGCM control run.

study of van Loon (1972). It certainly picks up the very strong first harmonic for the annual cycle over the African, Australian and South American continents well and the manner in which these spread over the neighbouring oceans. The simulation in the Indian Ocean is somewhat deficient. It shows a much stronger maximum than do the observations. In the South Pacific however the complex structure is reasonably well captured. High amplitudes are found downwind from the Australian continent, lower amplitudes exist in the lee of New Zealand and then greater amplitudes east of this. In the South Atlantic the model again does well capturing the strong amplitudes between the South American and African continents.

3. Comparison of semi-annual cycle between control and anomaly experiments

The above evaluation suggests the model is capturing the essence of the observed SAO, and hence is likely to be appropriately representing the relevant physics. With this knowledge, we are confident that the model will be able to provide realistic assessment of the effect on the SAO of changes in the boundary conditions. As indicated earlier we are interested here in the role of Antarctic topography and of sea ice in determining the characteristics of the SAO and it is around these two surface boundary conditions that we design our sensitivity studies. The first experiment reduces the Antarctic topography to sea level (although the continent is still regarded as snow covered land). All other parts of the model remain the same. This experiment has been given the acronym TOP. The next experiment is run as the control except that the sea ice surrounding the continent is removed. The temperature of the ocean is set to -1.8°C for simplicity. This experiment will be referred to as ICE. A third anomaly run combines the previous two such that there is no elevated topography over Antarctica and also no sea ice. This will be referred to as TOPICE.

The anomaly experiments are run for a duration of 6 years.

The first experiment that we examine is the one designated TOP. The leveling of the Antarctic topography has made very substantial impacts on the distribution of amplitudes (Fig. 5a). The basic structure has been broken down, particularly in the Indian Ocean where the characteristic signal of a minima at around 55°S separating two very zonally uniform maxima has now become quite noisy and virtually disappeared. The maximum in amplitudes that was present in the Weddell Sea has now split and been replaced by a minima with adjacent maxima. The only feature that has remained and appears quite stable is the maximum southeast of New Zealand. However, it has been strengthened and now extends eastward well across the Tasman Sea and into southeast Australia. This region showed a minimum in amplitudes in the control. The variance that is now explained by the second harmonic (Fig. 5b) is demonstrated to be fairly negligible over the Antarctic continent and its immediate surrounds. There is some signal further equatorward (mainly centered around approximately 40°S). The fundamental structure, however, has changed.

The ICE experiment (where just sea ice is removed from the control) shows a fairly normal and possibly strengthened SAO (Fig. 6). The amplitudes over the continent have increased, while the signal over the ocean basins remains rather similar to the control. In the Indian Ocean for instance, we still see the characteristic zonal structure with a belt of minima across approximately 55°S and maxima equatorward of this. The zonal asymmetry in the South Pacific still exists although the maxima in the lee of New Zealand appears to have moved downstream about 20–30°. There is a more consistent amount of variance explained by the second harmonic over the continent than in the control experiment although it is almost identical in other areas (over the oceans). Generally, a more modest impact appears to have been made in comparison with the TOP experiment leading us to presume that there is less sensitivity of the SAO to sea ice than there is to the Antarctic topography.

In the next experiment (TOPICE) where both sea ice and topography are removed, the amplitudes of the second harmonic (Fig. 7a) appear quite large again over the Antarctic topography (this appears to be typical of when the sea ice is removed). For the surrounding oceans, the amplitudes do not bear much similarity to those for the control experiment. South of Australia, there is a large strong maximum which does not appear either in the observations or in the control experiment. In the Indian Ocean, there is little sign of the characteristic signal where we see maxima around the coast of Antarctica and then a band of minima around 55°S followed by minima equatorward of this. At a glance, the sum of the anomaly amplitudes in the TOP and ICE experiments looks like those in TOPICE. Because of the relatively linear response in the TOPICE experiment (summation of TOP and ICE) there is little point in detailed examination of this experiment. Even though there are a number of areas where this is not true, it is of interest that the response should be largely linear.

Two additional experiments were conducted where not only was the Antarctic topography leveled, but it was actually replaced by ocean. In the first of these, the ocean was ascribed a constant temperature of zero degrees Celsius. In the second experiment, a meridional temperature gradient was prescribed whereby the temperature at 60°S was 0°C but each grid box poleward was 1°C cooler so that the grid box at the pole has a temperature of -9°C. The responses in these two experiments were very similar to those obtained in TOP and thus the experiments will not be presented in the interest of brevity. They show many of the same features as Fig. 3. Hence the absence of the Antarctic landmass (as distinct from its topography did not significantly impact on the SAO).

4. Mechanisms for differences in anomaly experiments

It would appear from the foregoing examination of the amplitudes and variance explained by the harmonics in each of the experiments, that the removal of the Antarctic topography in most areas (with the exception of over the continent itself) has a more substantial impact than does the removal of the sea ice. The variance explained by the second harmonic is less and its distribution less organised in the experiments where topography is removed. In the ICE experiment, the variance explained is much the same over the oceans surrounding the continent although some-

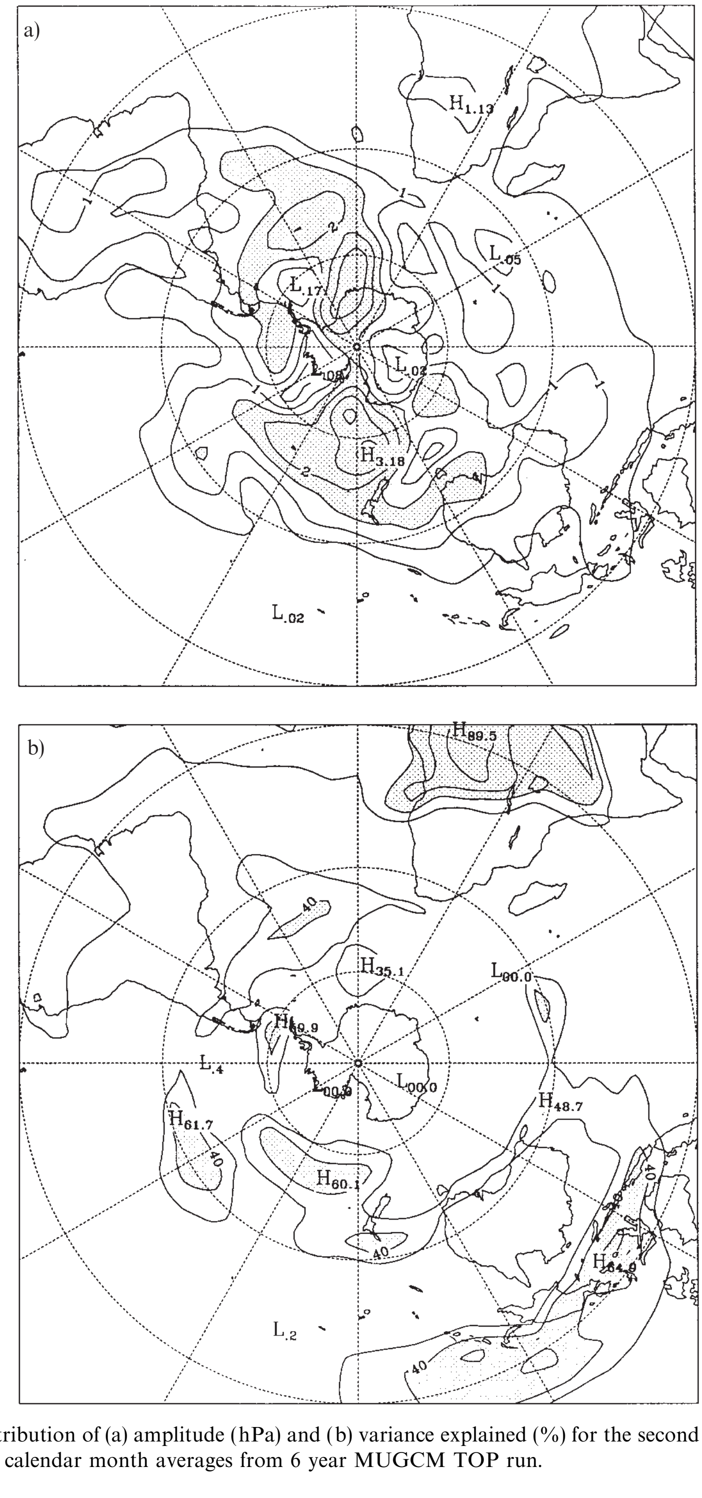
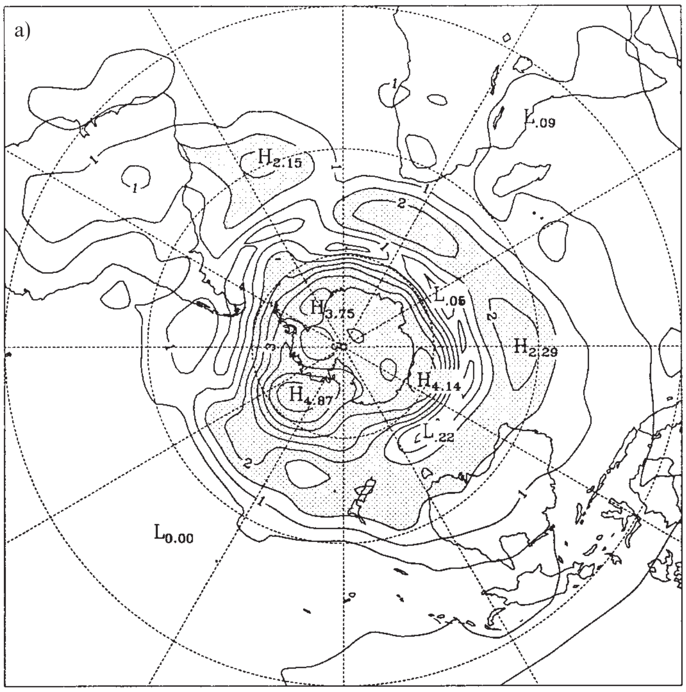


Fig. 5. Spatial distribution of (a) amplitude (hPa) and (b) variance explained (%) for the second harmonic of surface pressure based on calendar month averages from 6 year MUGCM TOP run.



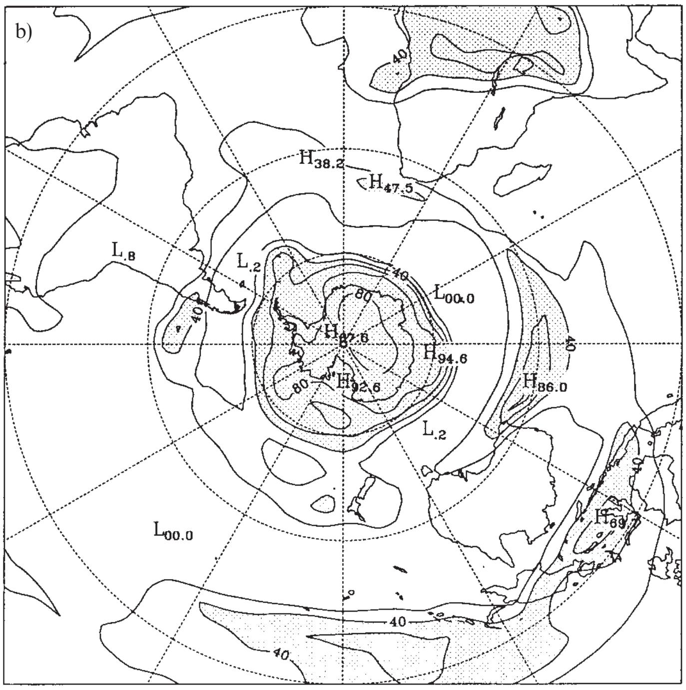


Fig. 6. Spatial distribution of (a) amplitude (hPa) and (b) variance explained (%) for the second harmonic of surface pressure based on calendar month averages from 6 year MUGCM ICE run.

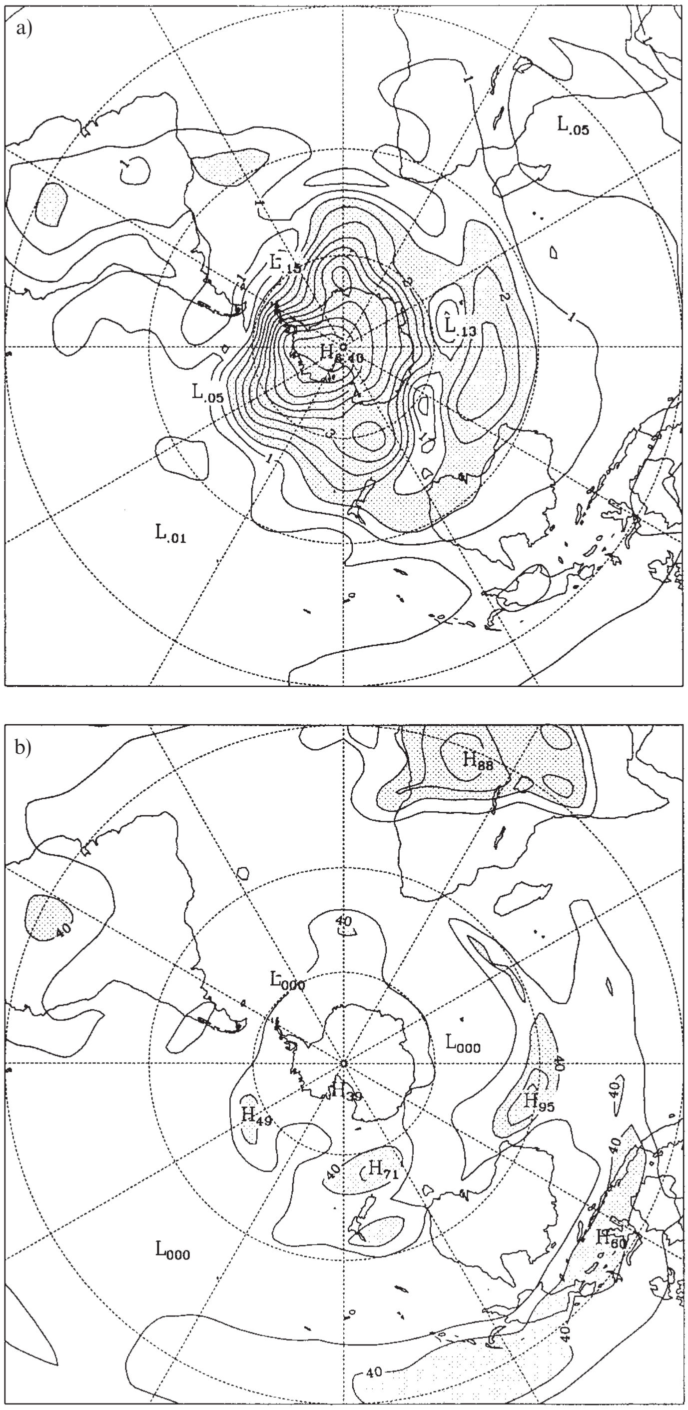


Fig. 7. Spatial distribution of (a) amplitude (hPa) and (b) variance explained (%) for the second harmonic of surface pressure based on calendar month averages from 6 year MUGCM TOPICE run.

what stronger over the continent. The primary explanation for the weakening of the variance explained by the second harmonic in the TOP experiment, yet strengthening over the continent in the ICE experiment, can be interpreted in terms of the behaviour of the first harmonic. In Fig. 8 we present the variance explained by the first harmonic in the TOP and ICE experiments. The first harmonic in the former bears considerable similarity to that in the CONTROL experiment (not shown) in most areas equatorward of about 50°S. There are substantial increases in variance explained by the first harmonic on and around the Antarctic continent for TOP compared with the control. In the ICE experiment, the variance explained by the first harmonic (Fig. 8b) is quite similar except on and around the continent where it virtually disappears. An increase in the variance explained by the first harmonic in any areas would tend to imply that the variance explained by the remaining harmonics (in this case the second harmonic) would likely be reduced (as there is less remaining variance to be explained). This is consistent with the changes in the distribution of the SAO for surface pressure that we see.

In each instance, the area where the greatest changes in the amplitude (or variance explained) of the first harmonic occur, is on and around the Antarctic continent. We wish to understand why the first harmonic for surface pressure should be stronger when the Antarctic continent is leveled and weaker when the sea ice is removed. The causes of this differing behaviour are revealed when we consider the zonal cross-section of temperature throughout the atmosphere. We compare the differences (TOP — CONTROL) and (ICE — CONTROL). The seasonal evolution of the anomalies for TOP are given in Fig. 9, where part (a) displays the summer (December to February) anomalies and (b) to (d) show Autumn, Winter and Spring anomalies respectively. We note that values near the surface (in the absence of the Antarctic landmass) are unreliable and thus have been shaded out as any anomalies will be heavily contaminated by the interpolation with height through the continent to sea level for temperature in the control experiment. From the pole to approximately 60–70°S in the middle-troposphere, we find that in summer, temperatures are somewhat lower in the TOP experiment than in the control. For the remainder of the year, temperatures are consistently higher in TOP with anomalies reaching four and five degrees.

In contrast, for the ICE experiment (Fig. 10), anomalies are very small (note the change in contour interval), generally less than 1 degree and do not show as much organisation (the strongest part of the signal is restricted to the lower atmosphere directly over the area of modified sea ice). Thus in terms of the temperature response, there has been a much greater impact in the TOP experiment and the annual cycle over the continent will certainly be changed. Assuming that the temperature over the surrounding oceans has been maintained, the temperature gradient between the oceans and the continent will also be modified and a change in the annual cycle of surface pressure will also then be implied. Harmonic analysis of this reveals a decrease in the second harmonic in the TOP experiment and an increase in the first. The opposite applies for the ICE experiment.

The key to understanding the response in the TOP experiment appears, then, to lie in the fundamental causes of the temperature anomalies simulated south of about 65°S. Simmonds and Law (1995) showed that, upon removal of the Antarctic landmass, cyclones were able to penetrate to deep southern latitudes in their "perpetual winter" numerical experiments. This is the key to the temperature response. With the exception of summer, when insolation forcing is quite strong, at these high latitudes, the surface energy budget can be thought of, largely, as a balance between emitted long-wave radiation and the advection of heat from lower latitudes (sourced from the relatively warm oceans). The penetrating cyclones bring with them a poleward transfer of heat which would lead to significant tropospheric warming throughout the year. This is consistent with the temperature changes that we see in the seasons Autumn through Spring. In summer the scenario is quite different. Insolation forcing is the main consideration. More cyclones penetrating the continent results in increased cloud cover as moisture from over the oceans is brought inland. In Fig. 11 we present the four seasons of zonally averaged anomalous total cloud cover for the TOP and ICE experiments. For TOP we see that particularly in summer, cloud cover is increased. In summer this will have a cooling effect. The increased cloud will readily reflect incoming solar

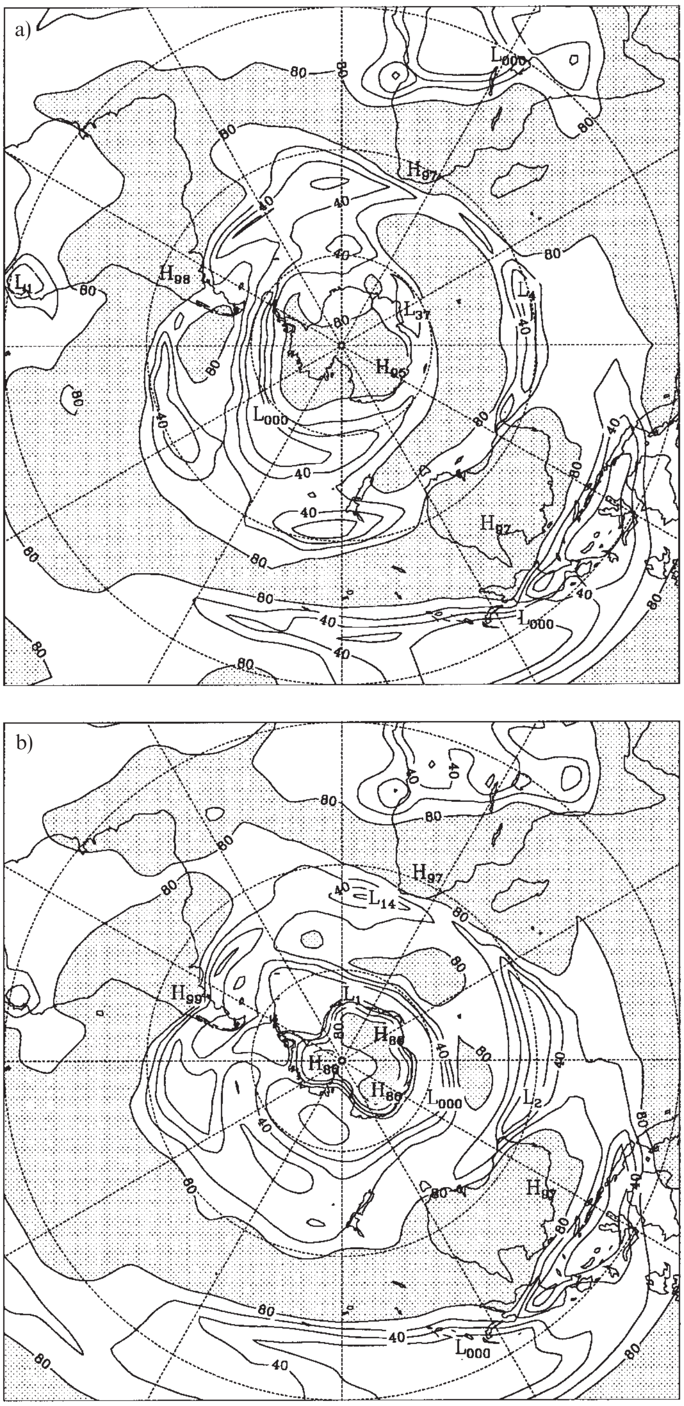


Fig. 8. Spatial distribution of variance explained (hPa) for the first harmonic of surface pressure based on calendar month averages from MUGCM (a) TOP and (b) ICE experiments.

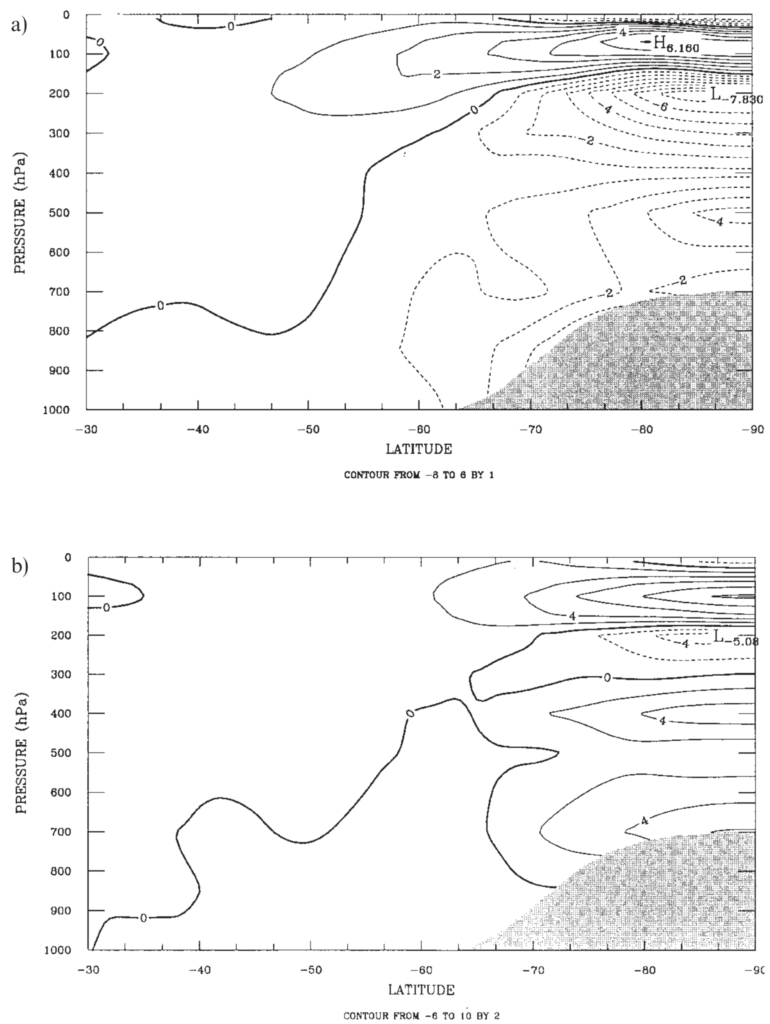


Fig. 9. Zonal cross-section of temperature anomalies from 30–90°S for (a) DJF, (b) MAM, (c) JJA and (d) SON (TOP —CONTROL).

radiation. In the other seasons the increase in cloud cover is not as great (one must remember the convergence of the meridians and thus the relatively small contribution that higher latitudes represent). However the reflecting potential of this cloud is much lower in these seasons because of the low incoming solar radiation. The increase in cloud cover, however, will have a substantial effect on the trapping of long wave radiation which will act to reinforce a warming of the atmosphere. The reflection of solar radiation in summer appears to dominate but in the other seasons when the insolation is small, the combination of the poleward transfer of heat with the extra cyclones and the increased trapping of longwave radiation due to greater cloud cover appears crucial.

A similar reasoning can be used in the ICE experiment. Although the anomalies are smaller, there is still a cooling in summer and a warming in the remaining seasons. Opening up the sea ice would promote a big increase in the latent heat flux from the ocean (Simmonds and Budd, 1991). This would obviously lead to increased cloud cover throughout the year and thus the same reasoning with blocking of sunlight in summer and trapping of longwave radiation in winter is applicable.

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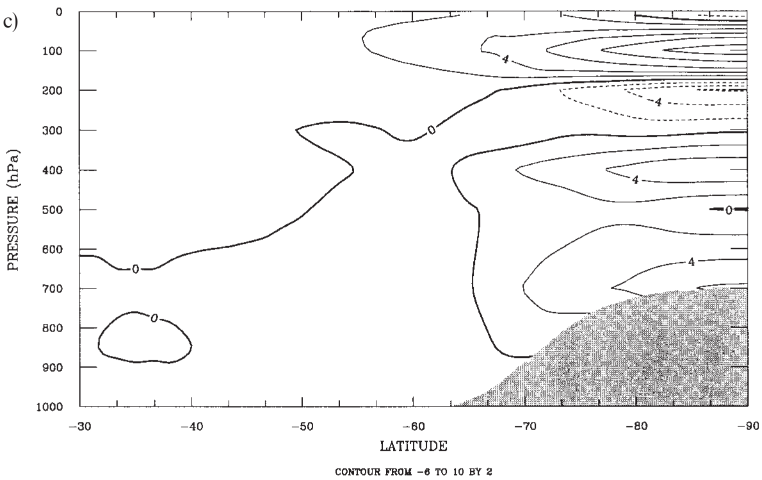

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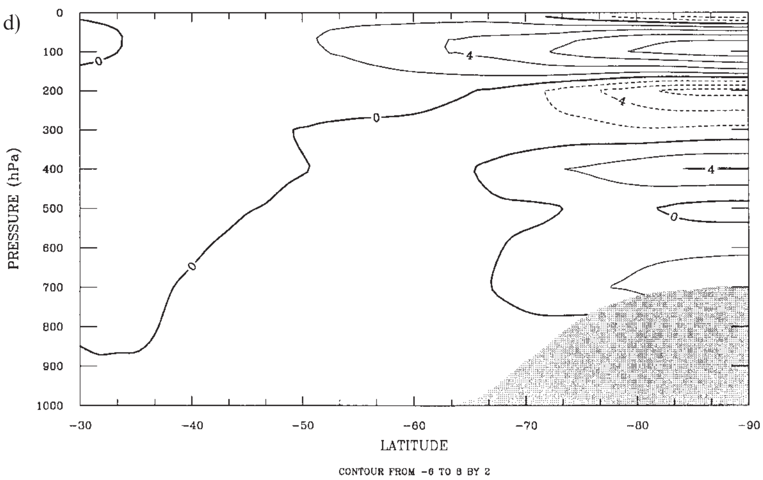


Fig. 9. (cont'd).

There have been several studies that have indicated that there is likely variability in the SAO on timescales varying from interannual, through decadal and even centennial, e.g. Simmonds and Walland (1998). In particular van Loon et al. (1993) and Simmonds and Jones (1998) have suggested that the observational record depicts trends in recent times whereby the SAO has weakened in the late 1970s after a period of quite strong SAO activity. Given the variability shown in the atmosphere in the southern extratropics on these timescales (Le Marshall and Kelly 1981; Swanson and Trenberth 1981; Enomoto 1991; Jones and Simmonds 1993), it is not so surprising to see an important feature of the Southern Hemisphere such as the SAO also varying on such timescales. It would be interesting to investigate whether or not large scale cloud cover over the Antarctic region also showed variability on these timescales and if so if the variability between the two was related. Our GCM experiments certainly seem to indicate that cloud cover forcing could be an important means leading to variability in the SAO. Observations, however may be very difficult to obtain. Large scale cloud records which we would need do not exist reliably for a very long period. Even station records (Russell-Head and Simmonds 1993) may not be representative of

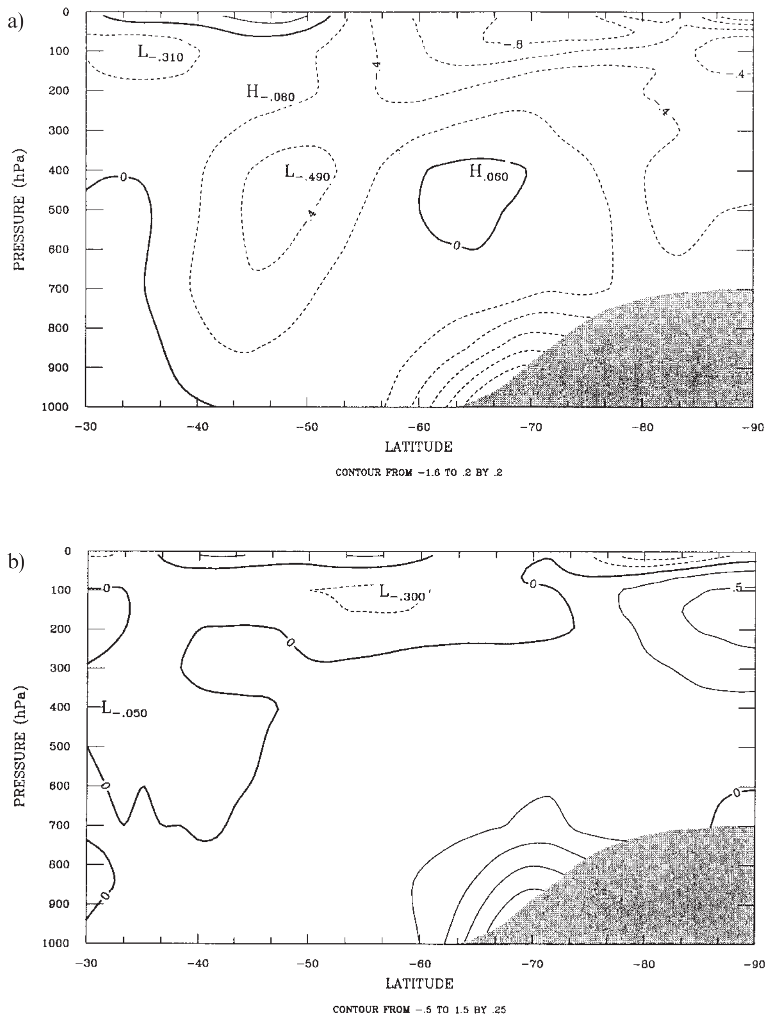


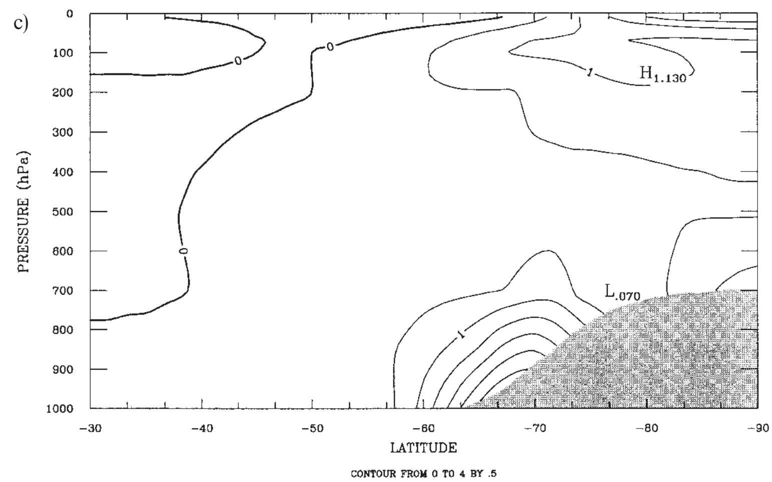
Fig. 10. Zonal cross-section of temperature anomalies from 30–90°S for (a) DJF, (b) MAM, (c) JJA and (d) SON (ICE — CONTROL).

larger spatial scales and, indeed, may not even be reliable in themselves (for example the taking of cloud "observations" in the polar night is fraught with inaccuracies). Satellite data are also prone to difficulties as the temperature at the surface is so cold that it is hard to distinguish between the cold cloud cover and the cold surface. This is something that may be examined in the future however.

5. Conclusions

We have integrated the Melbourne University General Circulation Model for twenty years and diagnosed from this its simulation of the semiannual oscillation of surface pressure. The model is shown to perform quite reasonably. While the amplitudes of the second harmonic in surface pressure variability are too weak compared with observations, the basic structure is captured. The simulation in the South Atlantic is shown to be somewhat different from the observations (basic structure looks to have moved equatorward some 10–20°) but in the Indian Ocean and western South Pacific in particular, the representation of the oscillation appears quite accurate.

To examine the sensitivity of the SAO, we design



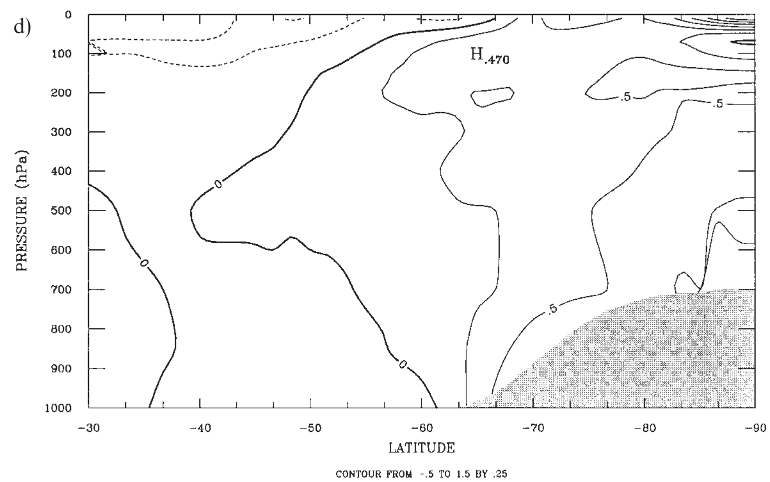


Fig. 10. (cont'd).

several anomaly experiments where the Antarctic landmass is reduced (to sea level) and the sea ice surrounding the Antarctic continent is removed. These experiments are integrated for a period of six years. The removal of the Antarctic landmass was shown to make significant differences. The basic structure of the amplitudes of the second harmonic was drastically changed in this sensitivity experiment and the variance explained by it was greatly reduced in most areas. The removal of sea ice made a more modest impact. Where the variance explained by the second harmonic in the TOP experiment was reduced, the variance explained by the first harmonic was enhanced and vice versa for the ICE experiment.

To reveal why the relative contribution of the first and second harmonics was being modified we examined the seasonal response of the zonally averaged temperature in the experiments. The TOP experiment proved to be much colder in the troposphere in summer but warmer in the rest of the year whereas the sea ice experiment showed only small anomalies (although in the same sense). This was understood for TOP in terms of the

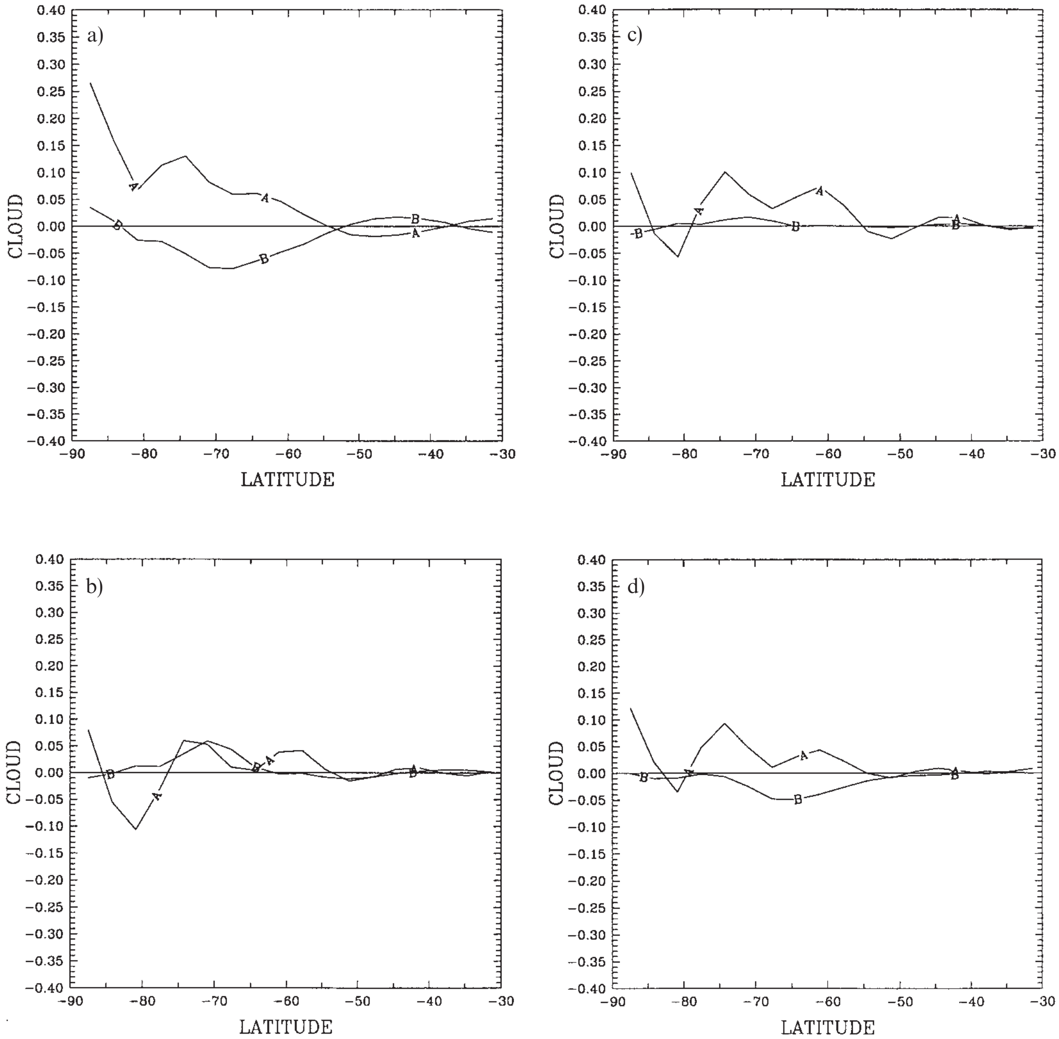


Fig. 11. Zonally averaged anomalous total cloud cover for (a) DJF, (b) MAM, (c) JJA and (d) SON for the TOP (A) and ICE (B) experiments.

increased penetration of cyclones over the continent without the barrier of the landmass. An increased transfer of heat and moisture took place now leading to warming for much of the year in TOP. In summer, however, the increased cloud cover associated with the cyclones, blocked out sufficient sunlight that a net cooling was observed. Similar arguments could be made in explaining the response in the sea ice experiment. When we open up the ice, an increased latent heat flux would lead to increased cloud throughout the year. In summer, this leads to cooling. In the remainder of the year because there is little or no insolation forcing the surface energy budget is in balance between long-wave radiation emitted from the surface and poleward advection of heat by weather systems. Increased cloud traps more long-wave radiation leading to warming of the troposphere. Thus it appears that the cloud forcing could be a very important means of inducing low frequency variability in the SAO of surface pressure at high southern latitudes.

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