Tellus (1998), 50A, 442–450
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TELLUS
ISSN 0280–6495

A modulation of the mechanism of the semiannual oscillation in the Southern Hemisphere

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(Manuscript received 3 November 1997; in final form 11 May 1998)

ABSTRACT

The local pressure changes associated with the twice-annual contraction/intensification and expansion/weakening of the circumpolar trough of low pressure around Antarctica, termed the semiannual oscillation (SAO), was the dominant signal in the annual cycle at mid and high southern latitudes before 1979. The mechanism, as shown by Van Loon (1967), arises from different response to the surface heat budget over the polar continent and the midlatitude ocean. It has subsequently been shown that in most years since 1979 the SAO has weakened considerably. Evidence is presented here from surface temperature data, 500 mb temperatures from a station pair and zonal mean 500 mb temperatures from the NCAR/NCEP reanalyses to show that a warming trend since 1979 has not been evenly distributed through the year at each latitude. Thus an anomalous *change* in the temperature gradient between 50°S and 65°S, with peaks in roughly May and November, has modulated the mechanism that produces the SAO, with its peaks in March and September. Consequently, the magnitude of the SAO has decreased in the more recent period.

1. Introduction

The semiannual oscillation (SAO) at middle and high latitudes in the Southern Hemisphere (SH) occurs throughout the depth of the troposphere and is characterized at the surface by an expansion and weakening of the circumpolar trough of low pressure surrounding Antarctica from March to June and September to December, and by a contraction and intensification from June to September and December to March. This twice-yearly pulsation of the circumpolar trough is associated with similar fluctuations of tropospheric temperature gradients, heights, pressure, and winds at middle and high latitudes in the SH (Van Loon, 1967, 1972). At the surface the strongest westerly winds south of about 50S occur during March and September and north of about 50°S during June and December. Before 1979, the SAO explained more than 50% of the observed mean annual variance of sea level pressure over vast areas of the SH middle and high latitudes (Van Loon, 1972).

Van Loon and Rogers (1984) updated the original Van Loon (1967, 1972) results by showing SAO in individual years. Simmonds and Jones (1998) have shown characteristics of the SAO from the Australian analyses of SLP for the period 1973–1993. The SAO has been documented in ocean currents in the southern extratropics (Large and Van Loon, 1989) and in ocean wind stress at those latitudes (Trenberth et al., 1990). The SAO has also been described in general circulation models (GCMs) of the atmosphere (Weickmann and Chervin, 1988; Xu et al., 1990; Kitoh et al., 1990; Meehl, 1991; Tzeng et al., 1993). Meehl and

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† The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Albrecht (1988) showed in a GCM experiment that an intensification of the midtropospheric temperature gradient causes a deepening and poleward shift of the circumpolar trough of SLP around Antarctica. Manabe and Stouffer (1996) compared results from climate model experiments with an atmospheric GCM coupled to a non-dynamic slab ocean, and also to a dynamic ocean. Low frequency surface temperature variability over most of the globe was similar with the two ocean formulations except over the mid and high southern oceans. This implies the dynamical coupling between ocean and atmosphere is essential for producing the correct climate variability in those regions. An analysis of a global coupled GCM by Simmonds and Walland (1998) shows that this dynamical ocean-atmosphere coupling at mid and high southern latitudes is important for producing low frequency variability of the SAO in the model.

After 1979 the amplitude of the SAO decreased dramatically (Van Loon et al., 1993; Hurrell and Van Loon, 1994). We will first describe the behavior of the SAO prior to 1979 and the mechanism proposed by Van Loon (1967) to explain it. Then we will present evidence from limited observational data to suggest that a modulation of the original mechanism has likely been responsible for the reduction in magnitude of the SAO in the more recent period.

2. The semiannual oscillation in the Southern Hemisphere

The SAO is evident in long-term monthly mean maps of observed sea level pressure (SLP, Van Loon, 1972). The trough of lowest SLP is farthest south and deepest in March and September and farthest north and weakest in June and December. Associated with the inter-seasonal intensity and latitudinal movement of this band of minimum SLP are changes in the pressure over large regions between about 35°S and the pole where the inter-seasonal rise and fall of SLP is influenced by the changes of the tracks and intensity of individual cyclones. Fluctuations of the circumpolar trough are thus indicative of changes in overall cyclonic activity. The net effect is pressure changes over extensive areas of the SH, including the circumpolar trough. For example, Sinclair (1994) notes a semiannual cycle of cyclone activity at high southern latitudes.

The SAO is evident throughout the depth of the troposphere. For example, Van Loon (1972, Fig. 5.15) shows that the amplitude of the second harmonic in pressure gradients and zonal mean geostrophic wind increases with height in the troposphere. Van Loon (1967) noted a twice-yearly intensification of the mid-tropospheric temperature gradient between 50°S and 65°S (the first harmonic has small amplitude relative to the second) associated with the SAO in SLP. Thus, a useful index of the SAO, first used by Van Loon (1967), is the difference of the zonal mean 500-mb temperature between 50°S and 65°S. He showed that this index, indicative of the state of the SAO, was associated with the forcing of the phenomenon. The idea is that the twice-yearly intensification of the midtropospheric temperature gradient between the ocean-dominated middle latitudes and the polar continental latitudes is associated with a twice-yearly increase of storm activity and thus changes in intensity of the circumpolar trough.

The mechanism, as posed by Van Loon (1967), arises from the different slope of the annual curves of temperature over the midlatitude ocean and the polar continent and their nearly equal amplitudes in the midtroposphere. As seen in Fig. 1, this circumstance produces an intensification of the temperature gradient twice a year in the midtroposphere and can be linked to the phase and amplitudes of the first harmonics being about the same throughout the troposphere. The temperature difference between the two latitudes therefore has no first harmonic. The difference between the small second harmonics of the annual cycle, which are of nearly opposite phase, thus dominates the change in temperature gradient.

The SAO is clearly a coupled ocean-atmosphere phenomenon, and SSTs and the associated atmospheric response are crucial elements of the Van Loon mechanism. There currently exists considerable uncertainty regarding the atmospheric response to SST forcing in models. Some studies have concluded that the atmosphere is insensitive to SST forcing (Lau and Nath, 1994; Graham, 1994). However, other studies indicate that the atmosphere does respond in a significant way to SST forcing (Palmer and Sun, 1985; Brankovic et al., 1994; Latif and Barnett, 1996). The Van

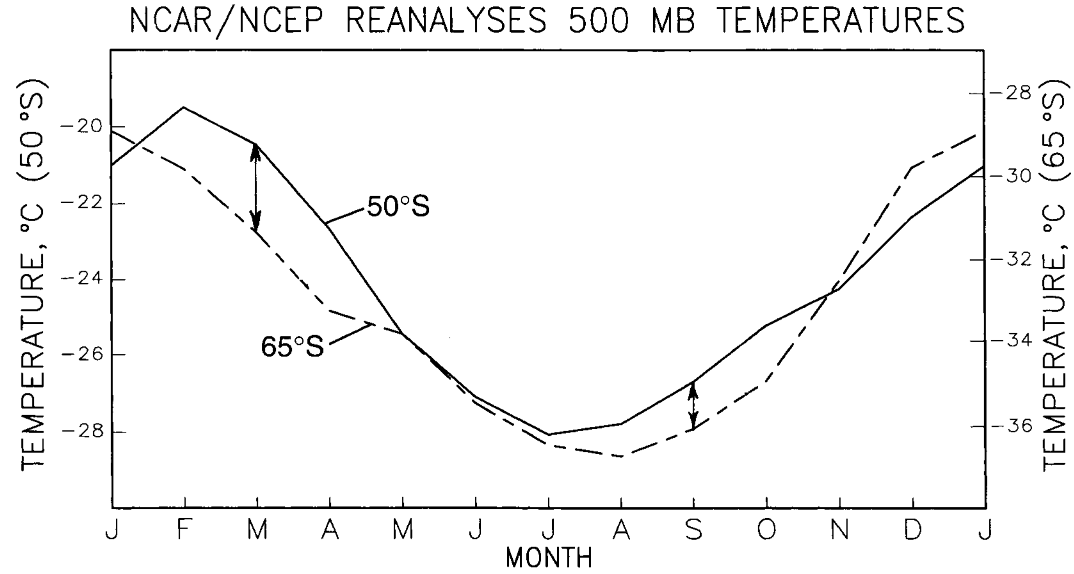

Fig. 1. Annual cycle of monthly zonal mean values of 500 mb temperature (°C) at 50°S and 65°S, from the NCAR/NCEP reanalyses from a period when the SAO amplitude was large 1973–79), superimposed to show the two times of year in the mean when the gradient between 50°S and 65°S intensifies (indicated by arrows), thus providing a manifestation of the SAO at middle and high southern latitudes. Solid line is 50°S (temperature scale at left); dashed line is 65°S (temperature scale at right).

Loon mechanism falls into the latter category, though this is still clearly a point of contention.

Meehl (1991) shows that in an atmospheric general circulation model (GCM) coupled to a simple non-dynamic ocean mixed layer (the MIX1 case), the annual cycle of SST at 50°S is not well reproduced, in part due to lack of a deep enough mixed layer with ocean dynamics to simulate accurately ocean heat storage. The annual maximum of SST occurs in March as observed, but the annual minimum falls in October, 2 to 3 months later than the observed annual minimum. This is also reflected at 500 mb in the MIX1 case. Nevertheless, the coreless winter (Van Loon, 1967) over Antarctica is reasonably well simulated in a qualitative sense. Therefore, the SAO in the MIX1 case has lower amplitude than both the observed SAO and from the same atmospheric model run with observed SSTs. This is mainly because of the different simulations of SSTs and ocean heat storage at 50°S. The first peak of SAO temperature gradient intensification still occurs in March-April as observed, but the second peak is much reduced. This causes a reduction of SAO amplitude in the MIX1 experiment mainly due to the delay of the annual SST minimum near 50°S by two to three months (Meehl, 1991, Figs. 4 and 6). This implies that a change of the seasonal cycle of SSTs at 50°S in the real system could alter the amplitude of the SAO.

3. Modulation of the mechanism of the SAO since 1979

As noted earlier, a change in the SAO was noted to have occurred around 1979 (Van Loon et al., 1993; Hurrell and Van Loon, 1994). This change in the seasonal cycle at mid and high southern latitudes is illustrated in Fig. 2 from Hurrell and Van Loon (1994). Zonal mean SLP at 50°S and 70°S are shown for the 1970s and the 1980s at top, with the difference, 50°S minus 70°S, shown at the bottom for the two periods. The difference of SLP at the two latitudes is a measure of the intensity of the wind between those latitudes, with large positive differences indicative of strong westerly wind. For the 1970s (the solid line at the bottom of Fig. 2), the two well-documented peaks of activity in the circumpolar trough in March

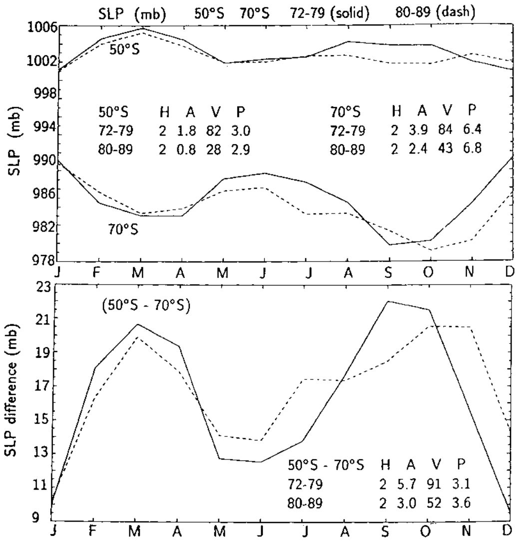

Fig. 2. Zonally averaged sea-level pressure (mb) for 50°S and 70°S (top) and their difference (bottom), averaged from 1972–79 (solid) and 1980–89 (dashed). Amplitude (A) in mb, percentage variance explained (V), and phase (P) in months are given for the second harmonics (H) (after Hurrell and Van Loon, 1994).

and September are clearly seen, with large positive values of the SLP difference at the two times of year when the trough contracts and intensifies as noted by Van Loon (1967). However, for the 1980s (the dashed line), there is a pronounced change in the seasonal cycle with greater values of the difference in May-June-July, decreased values in August-September-October, and greater values again in November-December. This index is indicative of baroclinicity between these two latitudes (and thus indicative of associated cyclonic activity), and these results therefore show that there was increased baroclinicity near the middle and end of the year in the 1980s compared to the 1970s, flattening the annual cycle of cyclonic activity and consequently decreasing the amplitude of the SAO in the later period compared to the earlier one. In other words, the second peak is delayed about 2 months in the later period and this has the effect of reducing the amplitude of the second harmonic.

Concerning possible causes for this change, Hurrell and Van Loon (1994) showed an association between the magnitude of the second harmonic of SLP at Chatham Island at 44°S east of New Zealand and SST anomalies in the tropical Pacific with positive SST anomalies associated with a decreased magnitude of the SAO at Chatham at decadal timescales. They suggested a possible modulation of the SAO from tropical convective heating anomalies implied by the tropical Pacific SST anomalies. However, as shown by Bottomly et al. (1990), the low frequency variability of SST anomalies in the tropical Pacific occurs with very similar character nearly globally, and as will be seen below, at other latitudes outside of the ones that are the primary focus of the Van Loon mechanism.

This brings us back to the original mechanism for the SAO proposed by Van Loon (1967), and the result from analysis of model experiments by Meehl (1991). That is, a change in the seasonal cycle of SSTs at the two key latitudes, the ocean-dominated latitude of roughly 50°S and the polar continental latitude near 65°S, could result in a modulation of the mechanism that produces the SAO. Thus, if there was an annual mean warming of SSTs near 50°S for the 1980s compared to the previous period, and if this annual mean warming was not evenly distributed throughout the year as suggested by Thomson, (1995) and Mann and Park, (1996), there could be a modulation of the Van Loon mechanism that could reduce the amplitude of the SAO.

To explore this hypothesis, we show surface temperature anomalies at 67.5°S from Jones (1994), and at 52.5°S from the GISST2 SST dataset (Parker et al., 1995). Note also the limitations to such datasets in the Southern Hemisphere (see discussion in IPCC (1996)). We use these data to provide evidence for a change in the annual cycle of surface temperatures at mid and high latitudes of the SH. Though data limitations mentioned earlier preclude definitive tests for significance of differences between the two periods, standard deviations are provided to give a sense of the relative amplitude of the anomalies. Additionally, it must be kept in mind that differences at any given latitude or month become important for the Van Loon mechanism when viewed as contributing to a change in gradient between 50°S and 65°S. For the GISST2 SSTs at 52.5°S, monthly standard deviations for the period 1980–94 range from about 0.1°C in May and June to over 0.2°C in August and November. At 67.5°S, monthly standard deviations computed for that same period range from summertime values of around 0.5°C, to wintertime values up to 1.9°C.

The annual cycle near the two key latitudes for the SAO mechanism is shown in Fig. 3. There is annual mean warming for the later period compared to the earlier period at both latitudes (+0.14°C at 52.5°S, and +0.22°C at 67.5°S). However, this annual mean warming is not distributed evenly throughout the year. At 67.5°S there is warming in the first part of the year greater than 0.4°C, and cooling of up to −0.5°C in November. SSTs at 52.5°S are mostly warmer in the more recent period by greater than +0.2°C with greatest warming of nearly +0.3°C in August.

As suggested by the Bottomly et al. (1990) results mentioned earlier, similar changes of the seasonal cycle of surface temperatures to those near 50°S occur at latitudes from roughly 45°S to near 60°S, while comparable changes in seasonal cycle at about 65°S are evident from south of 60°S to nearly 70°S (not shown, though the differences at two different latitudes, 47.5°S minus 62.5°S, and 52.5°S minus 67.5°S are shown to be similar in Fig. 6).

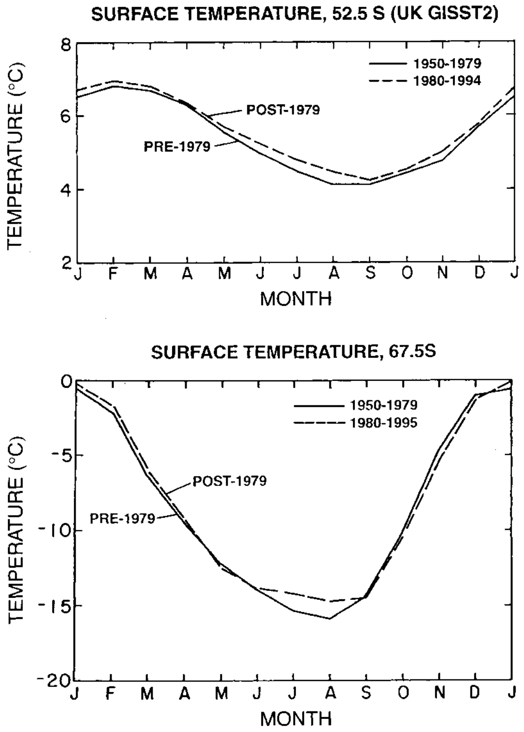

Fig. 3. Zonal mean surface temperature at 52.5°S from the GISST2 dataset (top), and at 67.5°S from the dataset of Jones (1994) (bottom); solid lines are averages for 1950–79, dashed lines for 1980–1995.

Since there could be problems with sampling in these datasets, it is useful to examine representative station data to see if a similar kind of change in the seasonal cycle at these two latitudes took place in the more recent period. As pointed out by Van Loon (1967) and Meehl (1991), the 500 mb temperatures are a good indicator of the midtropospheric temperature gradient associated with the SAO (Fig. 1). The 500 mb temperatures for the two periods are plotted in Fig. 4 for a pair of stations situated in positions representative of the two key latitudes, Marion Island (47°S, 38°E) and Davis (69°S, 78°E). Standard deviations for post-1979 monthly 500 mb temperatures are on the order of a degree. As in the surface temperatures in Fig. 3, the 500 mb temperatures for these two stations reflect similar changes, with annual mean warming for the post-1979 period (1980–93) compared to the earlier period (1951–1979) of +0.61°C at Marion with slight annual mean cooling (−0.05°C) at Davis (the years available for the earlier period at Davis are 1959–79). However, as was shown for the surface temperature data, there is greater warming in the first half of the year at both stations (around 1°C at Marion and a couple of tenths of a degree at Davis) for the more recent period compared to the earlier period, with relative cooling of several tenths of a degree at Davis in the latter part of the year. Though these absolute differences do not appear to be large compared to the monthly standard deviations, what is important is the differences of temperatures between the two latitudes and how those differences are distributed through the year, as will be discussed in Fig. 6.

Another way to check for changes of the 500 mb temperature gradient using a more uniform self-consistent dataset is to use the NCAR/NCEP reanalyses data (Kalnay et al., 1996). Monthly mean standard deviations of the zonal mean 500 mb temperatures range from about 0.4°C to near 0.8°C. Zonal mean 500 mb temperatures for the two periods are shown in Fig. 5 for the 1973–79 period and for 1980–95 for 50°S and 65°S. Averages in Fig. 5 are computed over somewhat different time periods than the station pair in Fig. 4, but are indicative of general pre- and post 1979 conditions and should also represent characteristics over a larger domain.

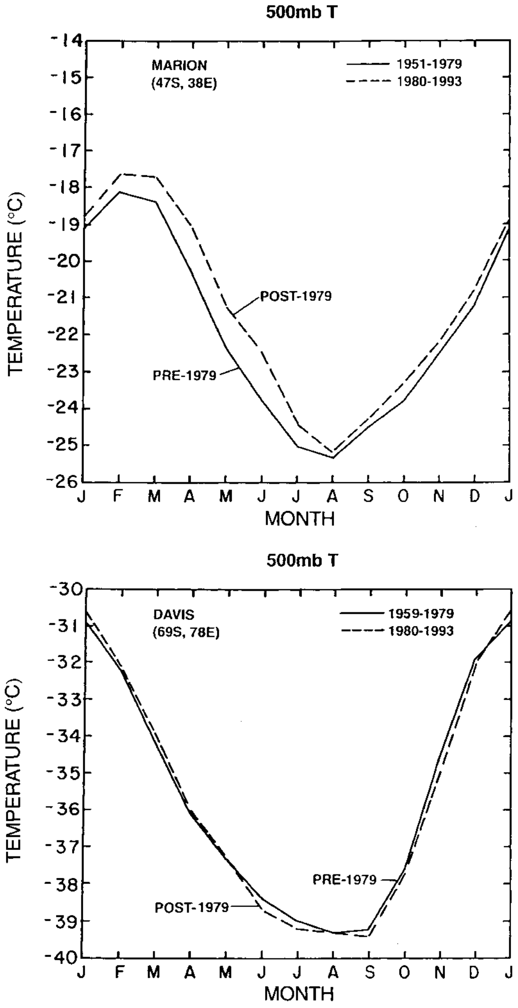

Fig. 4. Temperatures at 500 mb for two stations in the southern Indian Ocean, Marion Island near 47°S (top) and Davis near 69°S (bottom) averaged over 1951–79 for Marion and 1959–79 for Davis (solid) and 1980–93 for both (dashed).

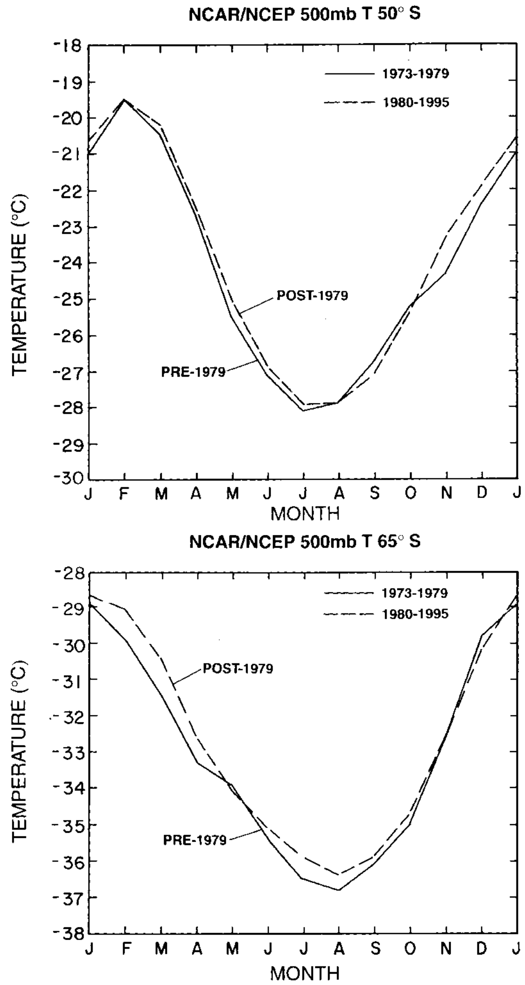

Fig. 5. Zonal mean temperatures at 500 mb from the NCAR/NCEP reanalyses averaged for the periods 1973–79 (solid) and 1980–95 (dashed) for 50°S (top) and 65°S (bottom).

The post-1979 temperatures are higher than pre-1979 in Fig. 5 at 50°S by several tenths of a degree in all months except September (−0.4°C) and October. Largest warming is evident in November (+1.03°C). At 65°S, the post-1979 temperatures are generally higher than pre-1979 during the first 10 months of the year by up to nearly 1.0°C in March (except for May), but show almost no change or slight decrease during November and December. The warming in September at 65°S (+0.3°C) and cooling of −0.4°C at 50°S, coupled with the warming of +1.0°C at 50°S and nearly no change at 65°S in November would have the effect of slackening the temperature gradient in the more recent period in September and intensifying it in November.

It was noted above for the station pair in Fig. 4 that warming in May-June and November-December at Marion (47°S) and cooling at Davis (69°S) for those same periods would have a similar effect, namely, to anomalously slacken the mid-

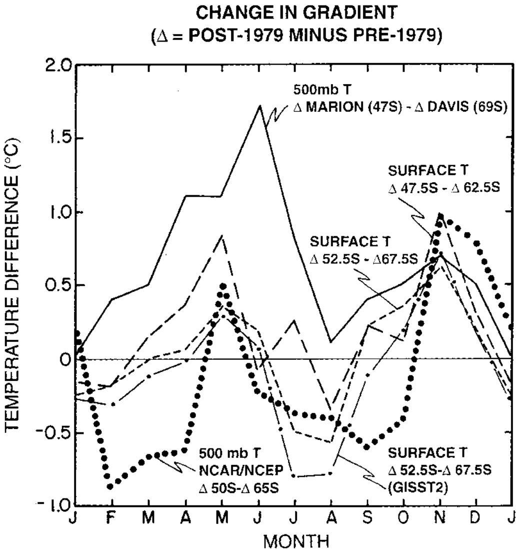

Fig. 6. Change in gradient for post-1979 minus pre-1979 for 500 mb temperatures, Marion minus Davis (solid line), for zonal mean 500 mb temperatures from the NCAR/NCEP reanalyses (dotted line), and for the zonal mean surface temperatures of Jones (1994) for 47.5°S minus 62.5°S (long dashed line), 52.5°S minus 67.5°S (short dashed line), and 52.5°S from GISST2 minus 67.5°S from Jones (1994) (dash-dot line).

tropospheric temperature gradient near September and intensify it around November.

A graphic illustration of the consequence of such changes of the annual cycle of monthly mean temperatures is illustrated in Fig. 6 which shows a plot of the difference in the temperature gradient between the two latitudes defined as

$$T_{\text{index}} = (\Delta\ T_{50\text{S}}) - (\Delta\ T_{65\text{S}}), \qquad (1)$$

where Δ is the the difference between the post-1979 minus pre-1979 temperatures. The dashed-dot lines in Fig. 6 are the latitude pair differences from 52.5°S minus 67.5°S as depicted in Fig. 3. To check for consistency the latitudes 47.5°S and 52.5°S from Bottomly et al. (1990) minus 62.5°S and 67.5°S, respectively, are also shown. For the surface temperatures, the station pair at 500 mb (solid line), and the zonal mean 500 mb temperatures from the reanalysis data (dotted line), there is an anomalous increase of the temperature gradient for the post-1979 period compared to the pre-1979 period near the middle and end of the year. These are the times of year noted in Fig. 2 to have a suggestion of increased gradient (wind) in the post-1979 period compared to the pre-1979 period. These limited data suggest that changes of the annual cycle of monthly mean surface temperatures, present through the depth of the troposphere, changed the 2nd harmonic of the temperature gradient between 50°S and 65°S in the more recent period. That is, the second harmonic of the change in temperature gradient between these two latitudes with May-November maxima modulates the climatological second harmonic with March-September maxima. The result is a flattening of the seasonal cycle of baroclinicity in the later period and a consequent reduction of SAO amplitude. This is similar to what occurred in the model simulation of Meehl (1991). That is, for example, a maximum in the gradient before about 1979 around September becomes reduced while a minimum in the gradient near November becomes a maximum. Thus secular changes in the amplitude of the SAO can be traced to a modulation of the seasonal cycle of surface temperatures near 50°S and 65°S that are an integral part of the SAO mechanism first proposed by Van Loon (1967).

One aspect of changes of the seasonal cycle of SLP differences between mid and high southern latitudes that does not relate as well to changes in temperature gradient according to the Van Loon mechanism occurs in July. Fig. 2 (bottom) shows increases of SLP gradient of about 3.5 mb, thus exceeding the increases in May and June. Though May and June both show evidence for increased temperature gradient in Fig. 6, July has less conclusive evidence for this relationship. Thus it is unclear as to what has caused the lower values of July SLP in the later period near 70°S (Fig. 2, top). Yet, the evidence for a shift of the temperature gradient maximum from September to November/December is consistent between the SLP and thermal data for those months. This remains the main contributor to the decrease of amplitude of the SAO in the later period.

5. Conclusions

The SAO is characterized by expansion and contraction of cyclonic activity in the mid and high southern latitudes twice a year, and was the dominant signal in the annual cycle prior to 1979.

The mechanism, as first proposed by Van Loon (1967), arises from the existence of a polar continent south of about 65S surrounded by ocean in middle latitudes, and the consequent different annual cycle of temperatures seen throughout the depth of the troposphere at those two latitudes.

A GCM with a weak SAO of the correct phase, when coupled to a simple non-dynamic slab ocean with an altered seasonal cycle of SSTs at 50°S and surface temperatures near 65°S, has an SAO of reduced amplitude suggesting that a change of the annual cycle of surface temperatures at the key latitudes of 50°S and 65°S could change the SAO (Meehl, 1991).

Results shown here of observations of surface temperatures, along with 500 mb temperatures from a station pair and zonal mean 500 mb temperatures from the NCAR/NCEP reanalyses, provides evidence that, in addition to annual mean surface warming since 1979 at both latitudes, the warming has not been uniformly distributed throughout the year. There has been greater warming in the first half of the year, and slight cooling during the later part of the year near 65S. Thus, the second harmonic of the change in temperature gradient in the post-1979 period with May–November maxima modulates the climatological second harmonic with March–September maxima in the pre-1979 period. The consequence is a reduction in amplitude of the SAO since 1979.

6. Acknowledgements

We thank Dennis Shea for his help with the station temperature data, and Julie Arblaster for her work with the GISST2 SSTs and NCAR/NCEP reanalysis data. A major part of this study was supported by the Office of Health and Environmental Research of the US Department of Energy under its Carbon Dioxide Research Program.

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