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A modulation of the atmospheric annual cycle in the Southern Hemisphere

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ABSTRACT

The annual cycle in pressure and winds at the middle and high latitudes of the Southern Hemisphere changed appreciably in the troposphere after the late 1970s. Before that time, its major component over most of the southern oceans and the Antarctic was a semiannual oscillation (SAO) which had maxima in the equinoctial seasons over the middle latitude oceans and in the solstitial seasons over the Antarctic south of 60° S. The SAO weakened after the late 1970s because of significant decadal changes in the monthly means primarily during the second half of the year. A result was that the polar vortex in the troposphere, which normally weakens after a peak in late September and early October, remained strong into November, and the breakdown of the stratospheric polar vortex was similarly delayed. The pressure in the circumpolar trough in the 1980s was generally lower than in the 1970s, which is similar to a documented change in the North Pacific during northern winter. We suggest that the changes in the SAO, the circumpolar trough, and the polar vortex are related to the concurrent rise of sea surface temperatures at low latitudes. The delayed breakdown of the polar vortex in the troposphere and lower stratosphere which happened after the late 1970s was coincident with the beginning of the ozone deficit in the Antarctic spring. This points to a strong dynamical influence on ozone amounts.

1. Introduction

The semiannual oscillation (SAO) in the middle and high latitudes of the Southern Hemisphere (SH) is an intrinsic component of the annual cycle forced by the dynamic coupling of the ocean and atmosphere (Van Loon, 1967; Meehl, 1991). Long-term station records show that the phase of the semiannual wave, unlike the phase of the annual wave, is comparatively stable and, therefore, the SAO dominates the long-term mean sea-level pressure (SLP) over large areas south of the subtropical ridge. This has been noted in the literature for more than 50 years, and Van Loon (1967) provides a list of many of the early studies of the SAO. Using the long-term climatological means in Taljaard et al. (1969), Van Loon (1972) presents spatial maps of the mean amplitude, phase and the percentage of variance of the annual cycle explained by the semiannual wave. The amplitude peaks from 45° S to 50° S in each of the three oceans, reaches a minimum near 60° S, and reaches a second peak over Antarctica. In regions where the amplitude peaks, the semiannual wave accounts for well over 50% of the total variance, and its share is more than 70% over large areas of the Indian and west Pacific Oceans. The phase changes at 60° S, from maxima in the spring and autumn in middle latitudes to maxima in the extreme seasons over the Antarctic. The phase change results in maximum meridional pressure gradients in March and September near 60° S and, thus, in a double wave in the zonal geostrophic wind and surface wind stress with a peak amplitude between 55° S and 65° S (Large and Van Loon, 1989; Trenberth et al., 1990).

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North of 50° S the phase of the semiannual wave in the wind is the reverse of that to the south (Van Loon, 1972).

Some of these characteristics of the SAO are illustrated in Fig. 1, which shows the long-term annual cycle of SLP at Chatham Island (44° S, 177° W) and D'Urville (67° S, 140° E). The first two harmonics explain over 90% of the mean annual variance at these stations with the second harmonic dominating. Van Loon and Rogers (1984a) present similar information for five other stations with long records between 38° S and 52° S and three other stations south of 65° S. In addition, they describe the interannual variability of the semiannual wave in the SLP and zonal geostrophic wind and note that, although in single years the second harmonic can be smaller than one or more of the other harmonics, it is easily identifiable in each year they examined. Moreover, because the phases of the other harmonics are highly variable from one year to another, the consistent phase of the semiannual wave allows it to dominate the long-term mean of pressure and wind. More recently, however, evidence has emerged which suggests that a low-frequency change occurred in the semiannual wave in the middle and high latitudes of the SH. Van Loon et al. (1993) describe a pronounced change that occurred in the annual cycle in the SH after the late 1970s. Using mainly zonal-mean statistics, they show that the semiannual component of the circulation weakened considerably and disappeared in the Pacific Ocean after the late 1970s and that this change was related to concurrent trends in the central pressures of the circumpolar trough and subtropical ridge.

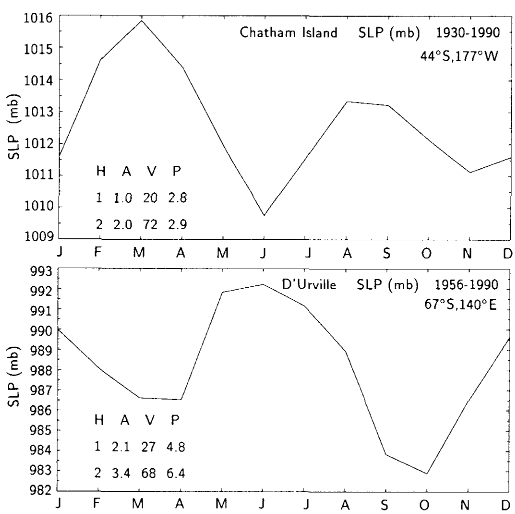

Fig. 1. Annual cycle of sea-level pressure at Chatham Island and D'Urville. Amplitude (A) in mb, percentage variance explained (V), and phase (P) in months are given for the first and second harmonics (H).

The purpose of this paper is to document this change in greater detail; namely, we will expand upon the zonal-mean harmonic analyses of Van Loon et al. (1993) and examine local changes in the semiannual wave, as well as document the changes in the annual cycle, as opposed to the changes in the harmonics. In addition, we will attempt to place the change that began in the late 1970s in a historical context, since it is important to determine if similar changes have taken place previously, or if the changes during the last decade are unprecedented in the data record. Given the paucity of data in the SH, this is a difficult question to answer completely, yet our results illustrate the danger of interpreting statistics from only a few decades as being representative of a stable climate state. Finally, we will present evidence which suggests that this change was not confined to the surface climate, but also occurred throughout the depth of the troposphere and extended into at least the lower stratosphere.

2. Historical station data

Earlier studies used widely dispersed stations to describe the influence of the SAO on the mean circulation of the SH (e.g., Van Loon, 1967; 1972). This was adequate because the semiannual wave dominated the annual cycle in the long-term station data over vast geographic regions. These same data can be used to place the change documented in Van Loon et al. (1993) in a historical context.

Fig. 2 presents the annual cycle of SLP at New Amsterdam Island (38° S, 78° E). The SAO has historically been strong from 40° S to 50° S in the Indian Ocean (Van Loon, 1972), where it reaches a maximum amplitude over 3.0 mb and accounts for nearly 80% of the total variance. Although north of the latitudes of the maximum amplitude, the long-term (1951–1979) mean SLP at New Amsterdam Island reflects the strong semiannual wave, where the second harmonic accounts for

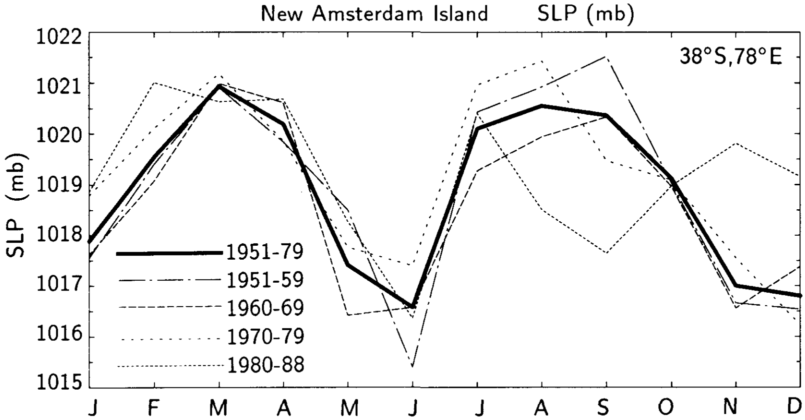

Fig. 2. Annual cycle of sea-level pressure at New Amsterdam Island for the long-term average and individual decades. See Table 1 for further details.

82% of the total variance and reaches an amplitude of 2.0 mb (Table 1). We have also plotted the mean annual cycle for each decade at New Amsterdam Island in Fig. 2, since the objective of this paper is to describe a low-frequency change in the SAO. Indeed, the amplitude of the SAO at a particular point can exhibit considerable variability from year-to-year.

During the three decades leading up to the 1980s, the second harmonic dominated the mean annual cycle of SLP and accounted for between 73% and 79% of the total variance. During the 1980s, however, the second harmonic accounted for only 11% of the total variance, and the amplitude was reduced to 0.6 mb (Table 1). Compared to previous decades, the change in the semiannual wave in the 1980s is seen to result primarily from the second (winter/spring) half of the year. In particular, the second maximum in SLP in late winter and the minimum in November/December are seen to disappear, implying a change in the movement and intensity of the circumpolar trough compared to previous decades (Van Loon et al., 1993). The trough extended farther north during September than in previous decades, while the opposite occurred during November/December (see also Fig. 8). From January through July, the monthly progression of SLP showed little change at New Amsterdam Island.

A similar analysis is presented in Table 1 for two other stations, Chatham Island in the Pacific and

Table 1. *Amplitude (mb), percentage variance explained, and phase (months) of the second harmonic of sea-level pressure for long-term averages and individual decades*

Station	Amplitude (mb)	Percent variance	Phase
New Amsterdam Island (38°S, 78°E)			
1951–1979	2.0	82	2.7
1951–1959	2.3	77	2.8
1960–1969	2.0	79	2.8
1970–1979	1.9	73	2.5
1980–1988	0.6	11	2.8
Chatham Island (44°S, 177°W)			
1930–1979	2.3	78	2.8
1930–1939	2.6	57	3.6
1940–1949	1.8	50	2.7
1950–1959	3.6	81	2.6
1960–1969	1.9	55	2.7
1970–1979	2.2	45	2.7
1980–1989	0.9	13	3.3
Gough Island (40°S, 10°W)			
1956–1979	1.7	74	2.8
1960–1969	1.6	66	2.8
1970–1979	2.3	65	2.7
1980–1989	0.9	11	2.8

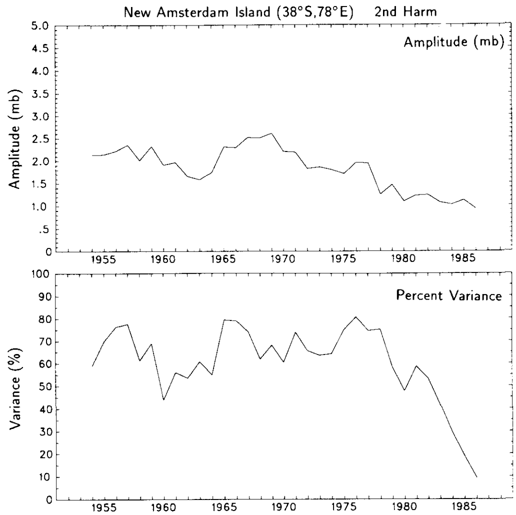

Fig. 3. Time series of the amplitude (top) and percentage variance explained (bottom) of the second harmonic at New Amsterdam Island from 7-year running means of sea-level pressure.

explaining from 45% of the total variance in the 1970s to 81% of the total variance in the 1950s. During the 1980s, however, a marked drop in both the amplitude and percentage of the variance explained by the second harmonic occurred. Similar results are seen in the Atlantic as represented by Gough Island.

To illustrate the change without limiting the analysis to only the decadal averages just presented, Fig. 3 shows the amplitude and the percentage of variance accounted for by the second harmonic at New Amsterdam Island and

Gough Island (40° S, 10° W) in the Atlantic. The long-term (1930–1990) mean annual cycle of SLP was presented in Fig. 1 for Chatham Island, which is located in a region where the SAO is more variable on interannual and longer time scales than in the Indian and Atlantic Oceans. Nonetheless, Table 1 illustrates that the second harmonic has always been strong at Chatham Island,

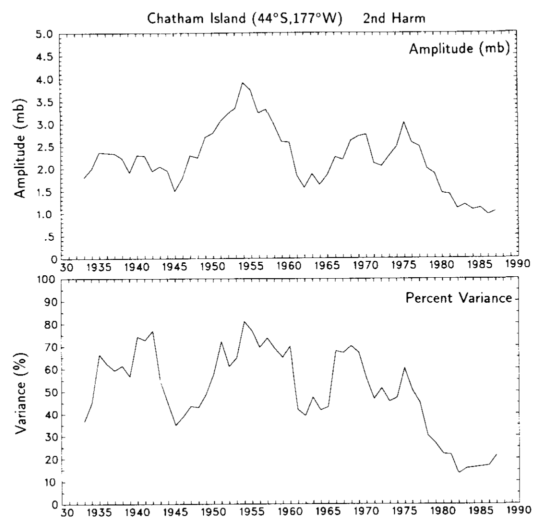

Fig. 4. As in Fig. 3, but for Chatham Island.

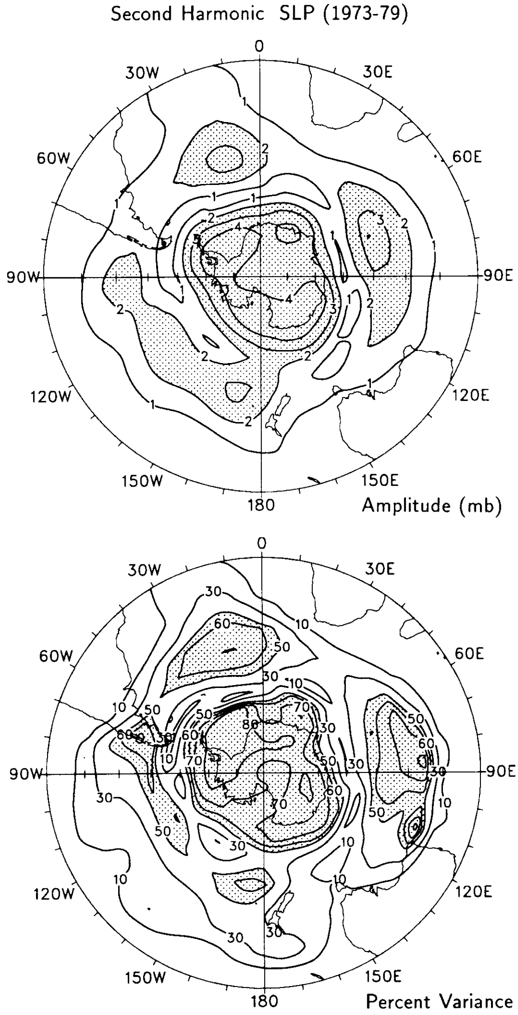

Fig. 5. Amplitude (top) and percentage variance explained (bottom) of the second harmonic of sea-level pressure averaged from 1973–1979.

harmonic at New Amsterdam Island from 7-year running mean annual cycles of SLP. A 7-year running mean was selected to emphasize the longer time scales over which the SAO has previously been strong, without losing too much of the data at the beginning and end of the period. From the mid 1950s until about 1977, the amplitude of the second harmonic at New Amsterdam Island was near 2.0 mb, and the percentage of the total variance explained averaged about 70%. By the 1980s, however, both of these statistics exhibited the lowest values during the period of record. A similar plot was presented for the amplitude at Chatham Island since the mid 1950s in Van Loon et al. (1993), but Fig. 4 shows the record extended back to the early 1930s and presents the percentage of variance explained as well. As stated earlier, Chatham Island is located in an area where the semiannual wave exhibits more variability also on a decadal time scale. The percentage of variance explained by the second harmonic varies from about 40% to 80% from the early 1930s until the late 1970s; during the 1980s, however, the percentage of variance explained was near 15% and the amplitude was less than in previous periods. At both New Amsterdam Island and Chatham Island, the phase of the second harmonic (not shown) varied little throughout the period. The results presented in Figs. 3 and 4 are typical of other stations in the middle latitudes of the SH with records of similar length.

3. Gridded analyses of SLP

The following analyses are based on daily operational maps from the Australian Bureau of Meteorology, which have been processed into monthly means. These analyses have been used, for example, to document the mean state (e.g., Trenberth, 1980; Karoly et al., 1986), observed eddy statistics (e.g., Van Loon, 1980; Trenberth, 1981a, 1982), and interannual variations (e.g., Trenberth, 1981b, 1984; Kidson, 1988) of the SH circulation. The quality of these data have been discussed by Trenberth (1981a, b) and Swanson and Trenberth (1981), who noted that the 0000 UTC surface pressure and 500 mb geopotential height charts are the most reliable. Consequently, we have confined our analyses to those data.

Shown in Fig. 5 is the amplitude and the percentage of variance explained by the second harmonic of the annual cycle of SLP averaged over the period 1973–1979. It is noteworthy that the pattern of the SAO during the 1970s is very similar to earlier analyses of the semiannual wave based on station data (Van Loon, 1972). Peak amplitudes occur in all three oceans near 50° S, minima are found near 60° S, and a peak is noted over Antarctica. In the regions of peak amplitude, the semiannual wave accounts for more than 50% of the total variance. The same plots for the period 1980–1989 (Fig. 6) illustrate the strong reduction in the amplitude of the wave: a weak peak near

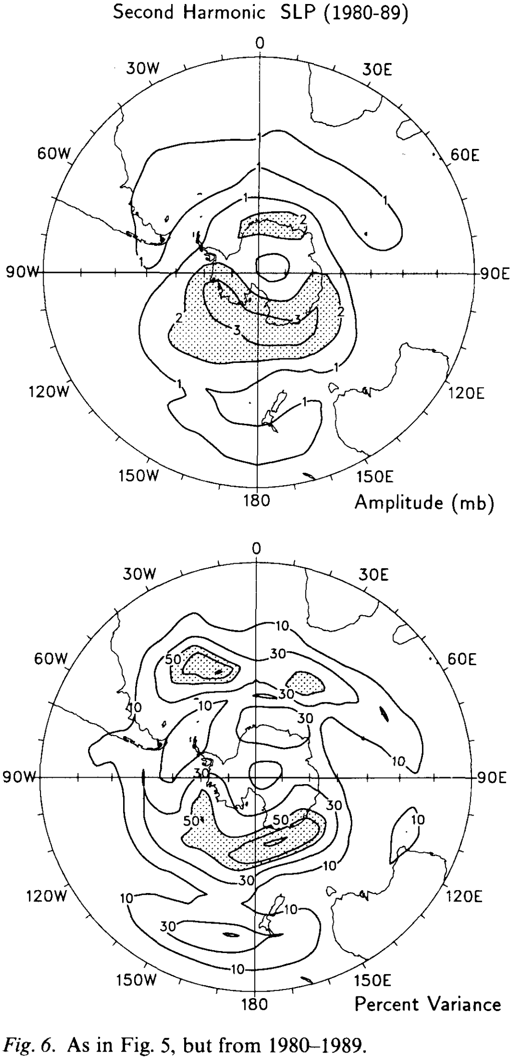

Fig. 6. As in Fig. 5, but from 1980–1989.

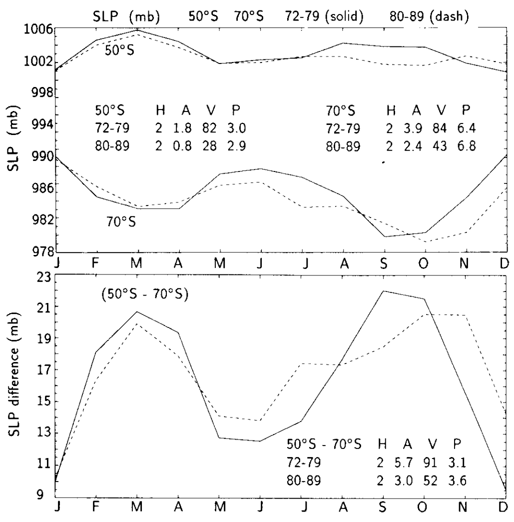

Fig. 7. Zonally-averaged sea-level pressure (mb) for 50° S and 70° S (top) and their difference (bottom), averaged from 1972–1979 (solid) and 1980–1989 (dash). Notation is the same as in Fig. 1.

50° S extends across the Atlantic into the western Indian Ocean with a minimum to the south near 60° S. From near 80° E eastward across the middle latitudes of the Pacific, however, the mid-latitude semiannual wave is very weak or has disappeared. Strong reductions in the percent of total variance explained by the SAO are also evident in Fig. 6 across the middle latitudes of the SH and over the Antarctic.

The change in the SAO is further illustrated in Fig. 7, which shows the annual cycle of zonal mean SLP at 50° S and 70° S averaged over 1972–1979* and 1980–1989. These latitudes were chosen because each is near the mean latitude of the peak of the semiannual wave in its opposing phases (see, Fig. 5 and Van Loon, 1972, Fig. 4.10). The amplitude, percentage of variance explained, and the phase of the second harmonic are also given in the figure for each period. During the 1970s the zonal mean SLP at 50° S and 70° S is very similar to earlier analyses based on station data, with a strong semiannual wave evident. For example, the results of Van Loon (1972) show that the second harmonic of the zonally-averaged SLP at 50° S explained over 90% of the total variance. It is also notable that the change in the zonal mean at 50° S is similar to that at New Amsterdam Island (Fig. 2). In particular, the second maximum in September/October and the minimum in November/December disappear, while there is very little change between the decades in the mean SLP from January through July. Changes in the zonally-averaged monthly mean SLP between the 1970s and the 1980s are significant at the 5% level for the months of September and October.

At 70° S, pressures were lower in the 1980s in general over the winter and spring seasons, although because of large interannual variability only the change in November proves to be significant at the 5% level. It also appears that the lowest pressure of the circumpolar trough in spring was delayed by one month from September/October in the 1970s to October/November in the 1980s. The accompanying one month delay in the strongest surface zonal geostrophic wind is shown by the annual cycle of the SLP gradient between the two latitude belts, which is also given in Fig. 7. This pressure difference spans a small part of the Antarctic easterlies as well the subantarctic westerlies since the lowest pressure in the circumpolar trough in the zonal and annual mean is near 66° S, with extreme monthly mean positions within 3° of that latitude (Van Loon, 1972; Van Loon et al., 1993). The zonally-averaged position and lowest pressure of the center of the circumpolar trough was examined by Van Loon et al. (1993). They noted that the trough was deeper and farther north on average in the 1980s compared to the 1970s; however, their use of 12-month running means masks the month-to-month changes evident in Fig. 7.

To show further how the semiannual wave weakened in the 1980s, the differences in SLP between the decades for the months of September/October and November/December are presented in Fig. 8. Stippled regions indicate differences in the means with local significance at the 5% level. Previous studies of the semiannual wave have noted that, since the wave explains such a large percentage of the annual variance in the SLP of the middle and high latitudes of the SH, it is easily discernible in the interseasonal change of pressure (e.g., Van Loon and Rogers, 1984a). This is not true of the 1980s during southern winter and

* The gridded analyses begin in May 1972, so the January through April means are averaged over the seven years from 1973 through 1979.

spring. The reason for this is shown in Fig. 8, which indicates that winter and spring SLP differences between the decades are in a direction that is opposite the interseasonal changes documented in earlier studies. For example, the change in SLP from June to September shown in Fig. 1 of Van Loon and Rogers (1984a) is characterized by pressure rises over the three oceans between about 30° S and 60° S and pressure falls poleward

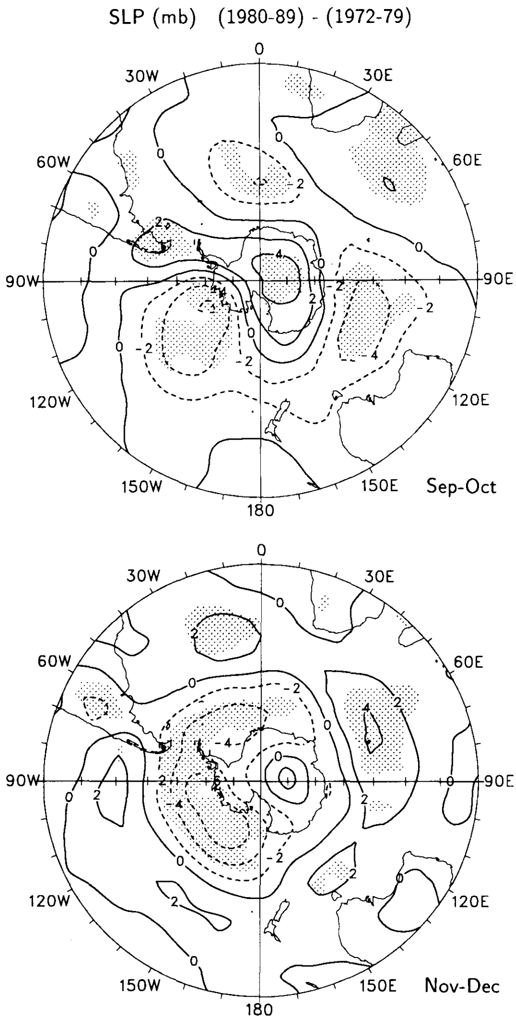

Fig. 8. The difference in sea-level pressure (mb) between 1980–1989 and 1972–1979 for September/October (top) and November/December (bottom). Values significantly different from zero at the 5% level using a *t*-test are stippled.

of about 60° S. This is indicative of a poleward contraction of cyclonic activity over the southern oceans. Opposite interseasonal changes take place when the trough expands equatorward from September to December. The decadal changes shown in Fig. 8 are opposite to those just described; namely, pressures were significantly lower (higher) in middle (high) latitudes during the 1980s compared to the 1970s in September/October, while the reverse occurred during November/December. Consequently, maps of interseasonal changes of SLP during the 1980s (not shown) reveal much smaller differences than those shown in Van Loon (1972) and Van Loon and Rogers (1984a). These changes account for the weakening of the semiannual wave during the most recent decade.

4. Upper-level analyses

Shown in Fig. 9 is the difference between the 1970s and 1980s at 500 mb during September/October and November/December. Notably, the changes are consistent with the SLP maps shown in Fig. 8. The increase in the November/December 500 mb height gradient between the middle and high latitudes of the SH is clear, and it implies a continued strong tropospheric polar vortex into late spring during the 1980s. The extent to which the late spring changes extend into the upper troposphere and lower stratosphere, as they should according to the thermal wind relationship, is more difficult to assess because of the general lack of high-quality data at such levels. Where possible, we have again relied upon station data.

The 100 mb and 50 mb heights at Casey (66° S, 111° E) are shown in Fig. 10 and are typical of the other station records located at high latitudes that we have examined. Time series of the interannual variability of only November heights are presented for Casey because of the relatively high frequency of missing years for December means*. Presented are anomalies, normalized by their standard deviation, constructed from a 1958–1991 mean at

* About 25% of the December monthly means were missing in the Casey record. When possible, however, the November/December means were computed and were found to be in excellent agreement with the variations of the November-only means.

100 mb and from a 1968–1991 mean at 50 mb. November means for 1966 and 1967 were extrapolated from surrounding stations, while data for 1986, 1987, 1988, and 1991 were obtained from an average of surrounding grid points taken from the global analyses produced by the European Centre for Medium Range Weather Forecasts (ECMWF). The quality of the ECMWF stratospheric analyses during these years has recently been discussed by Trenberth (1992), who found them to be most reliable after May 1986. The November data from ECMWF and Casey showed very close agreement in both 1989 and 1990.

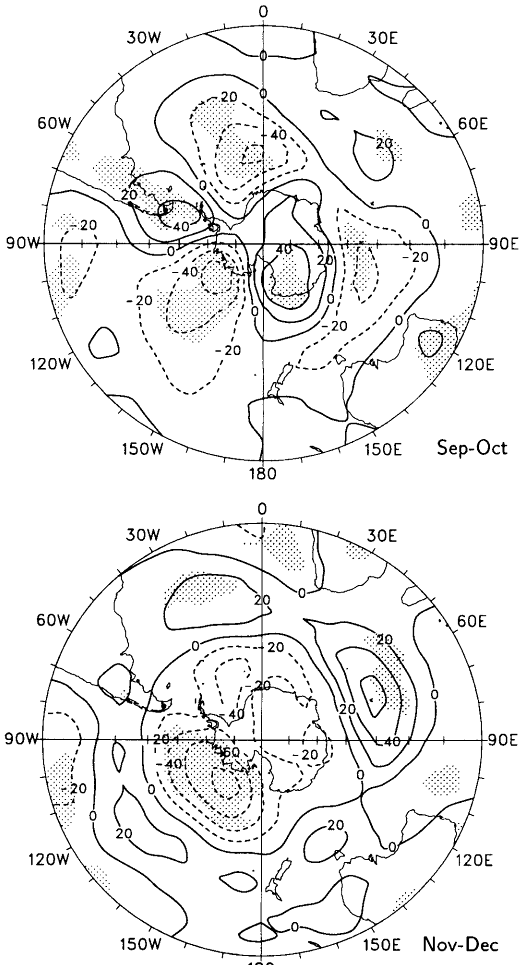

Fig. 9. As in Fig. 8, but for 500 mb geopotential heights (m).

The time series at Casey in Fig. 10 show a significant drop in the heights at both 100 mb and 50 mb beginning in the late 1970s. This is emphasized by the low pass curve that shows just how different the period of the 1980s has been (in relation to the relatively short record), even considering the large amount of interannual variability in the record. An almost biennial oscillation is apparent in the time series and is evidently widespread in the SH (e.g., Trenberth, 1975; Van Loon and Shea, 1987; Kiladis and Van Loon, 1988), and it is also clearly visible in the time series of the annually- and zonally-averaged lowest pressure in the circumpolar trough shown in Fig. 8b of Van Loon et al. (1993).

The time series of November temperatures at Casey are shown in Fig. 11. At 100 mb, the height and temperature fluctuations at Casey are in phase at all frequencies. Also shown are the interannual temperature changes at 300 mb, which again are in good agreement with those at 100 mb, especially at lower frequencies. However, the temperature time series at 50 mb does not reveal the low-frequency cooling during the 1980s evident at the lower levels, although the 50 mb heights are in phase at all frequencies with the 100 mb heights (Fig. 10).

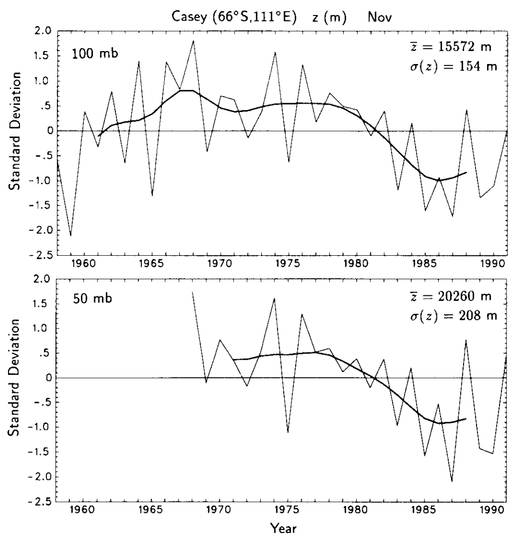

Fig. 10. Time series of 100 mb (top) and 50 mb (bottom) geopotential heights at Casey for November, smoothed with a low pass filter (heavy solid line). Shown are normalized anomalies relative to a 1958–1991 mean at 100 mb and a 1968–1991 mean at 50 mb.

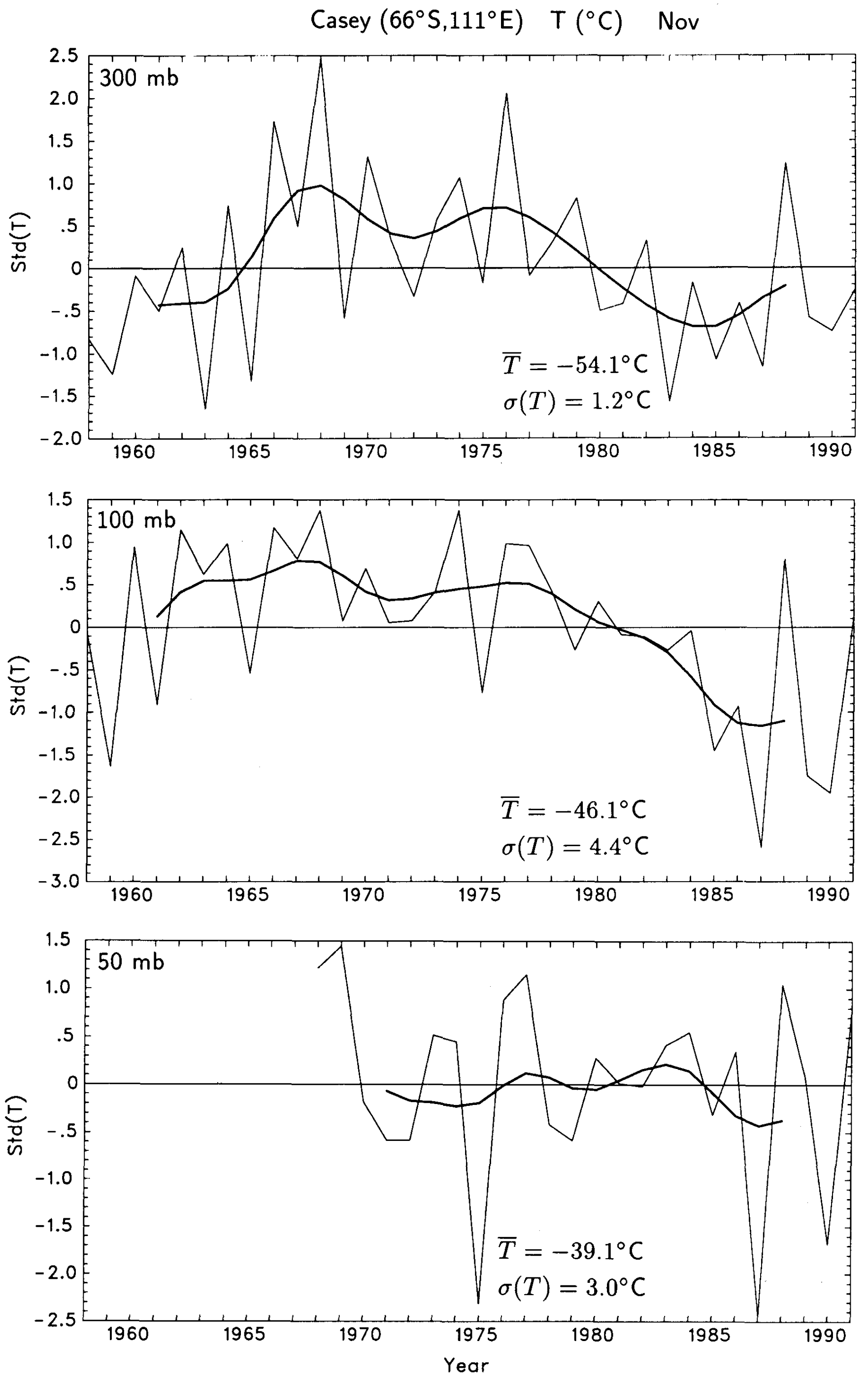

Fig. 11. As in Fig. 10, but for temperatures (C) including the 300 mb level. The anomalies at 300 mb are relative to a 1958–1991 mean.

This implies that the low frequency height falls at 50 mb at Casey reflect tropospheric circulation changes. Other Antarctic stations also lack well-defined trends in November 50 mb temperatures during the 1980s, although cooling trends are evident near 100 mb (see WMO, 1988; Newman and Randel, 1988).

A view of the spatial pattern of upper tropospheric and lower stratospheric height differences between the 1980s and earlier periods is difficult to obtain from historical station data, primarily because of large gaps in many of the observed upper-air records. To obtain an idea of what the change might have been, the November/December changes in 100 mb and 50 mb geopotential heights from two climatologies are presented in Fig. 12. The most recent data (1986–1991) are constructed from the ECMWF analyses. The climatology from 1968–1972 is from the atlas of Knittel (1976), who describes the circulation of the stratosphere of the SH for the 100 mb, 50 mb and 30 mb pressure levels. His climatology of five-year means of geopotential heights, temperatures, and geostrophic winds is based on an analysis of radiosonde measurements. The results shown in Fig. 12 are consistent with our analyses of station data; namely, they indicate considerably lower heights during November/December at both 100 mb and 50 mb over high latitudes of the SH during recent years, implying a continued strong polar vortex into late southern spring.

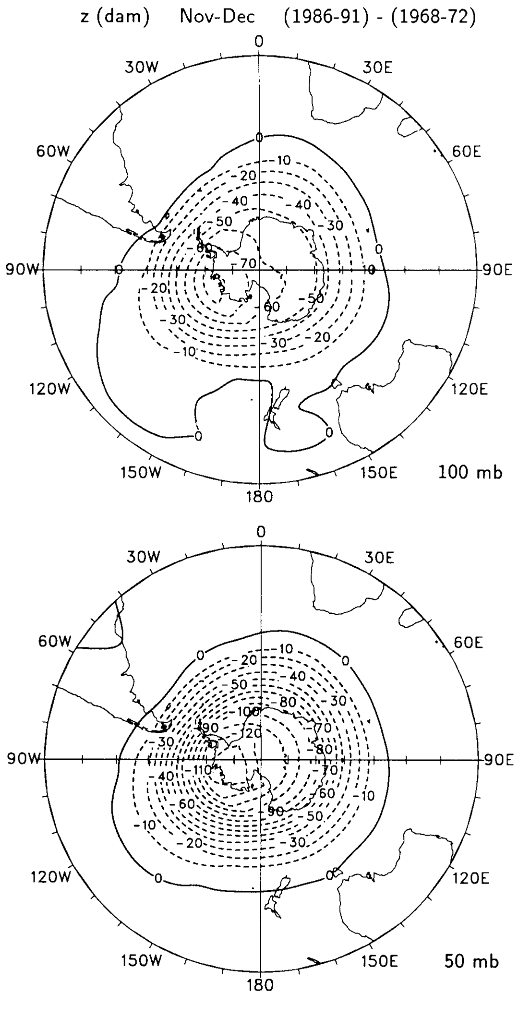

Fig. 12. Geopotential height differences (dam) for November/December at 100 mb (top) and 50 mb (bottom) between a 1986–1991 climatology from ECMWF and a 1968–1972 climatology from Knittel (1976).

5. Discussion and conclusions

Changes in the atmospheric circulation over time scales of decades are very difficult to quantify because of the sparsity of observational records. This is especially true of the SH. Before the Global Weather Experiment (GWE) in 1979, most of the knowledge of the main features of the SH circulation had been acquired partly from synoptic charts prepared during the period 1951–1963 in the South African Weather Bureau and partly from climatological maps (Taljaard et al., 1969). The hemispheric analyses available from the Australian Bureau of Meteorology beginning in May 1972 extend these analyses in time. Analyses of the annual cycle of SLP, winds and temperature of the SH using the Australian data from the 1970s (e.g., Van Loon and Rogers, 1984a, b) were similar in most respects to results of earlier studies based on the climatological maps (derived from station data) and daily synoptic maps (e.g., Van Loon, 1967, 1972). This is not true of the analyses of the 1980s, however, as shown by Van Loon et al. (1993).

This paper documents a change in the SH middle and high latitude circulation that began just before 1980 and disturbed the annual cycle, especially the semiannual component which was the dominant harmonic in earlier analyses. The major changes in the SLP and 500 mb height fields occurred in the winter and spring seasons. In middle latitudes over the three ocean basins during September/October, SLP and 500 mb heights were significantly lower during the 1980s compared to the 1970s, while higher pressures and heights were noted poleward of 60° S. Opposite conditions prevailed during November/December. These interdecadal changes are in the opposite sense to the interseasonal changes contained in the data records before 1980, such as the poleward contraction of the circumpolar trough from June to September and the equatorward expansion from September to December (Van Loon and Rogers, 1984a). Consequently, the winter and spring interseasonal transitions during the 1980s were damped, and the SAO was weakened. From the limited number of long-term station records available, changes similar in size to those that occurred during the 1980s were not found over the past 40 to 60 years. While such a conclusion is tentative because of the paucity of data, the results presented here do emphasize that climate statistics from only few decades may not be representative in many respects.

The causes for the change during the 1980s are difficult to assess. The influence of tropical sea surface temperatures (SSTs) on extratropical tropospheric circulations is well documented through both modeling and observational studies. Recently, Chen et al. (1992) and Trenberth and Hurrell (1994) have shown that a decadal time-scale variation in the tropospheric circulation of the North Pacific beginning in the late 1970s was linked to recent positive changes in the tropical SST. While it is reasonable to assume that a change also occurred in the SH circulation in response to the higher SSTs of the 1980s, the hypothesis is more difficult to prove because of the sparsity of data. Van Loon et al. (1993) show that the pressure in the circumpolar trough fell from the 1970s to the 1980s, and our analysis indicates that these falls were most pronounced during winter and spring, especially in the South Pacific. This result is consistent with the deepening of the Aleutian low during northern winter, which points toward an influence of the tropical SSTs on the polar low pressure areas of both hemispheres. Shown in Fig. 13 are seven year running means of annual SST anomalies, relative to a base period of 1951–1980, averaged over the tropical Pacific (180°–90° W, 10° S–5° N) and multiplied by minus one. The SSTs are superimposed on the amplitude of the second harmonic of the seven year running means of SLP from Chatham Island taken from Fig. 4. The SST anomalies are from Bottomley et al. (1990), and because of problems with data coverage in the tropics, are probably most representative after 1950. While only for one point

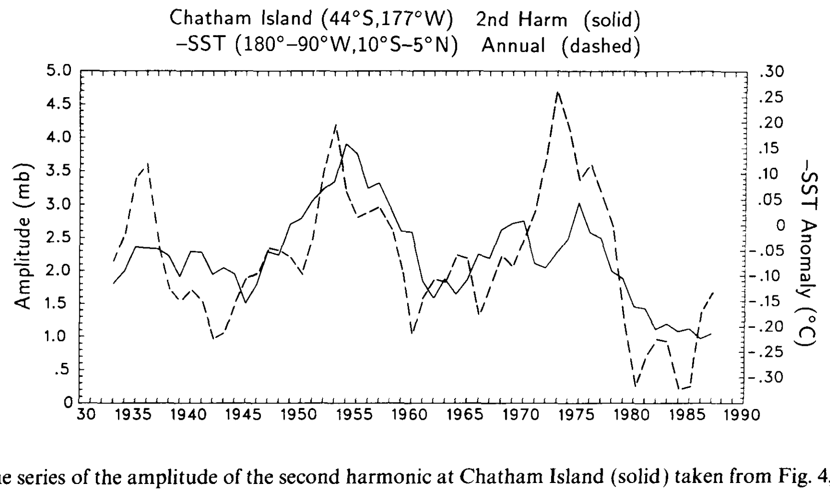

Fig. 13. Time series of the amplitude of the second harmonic at Chatham Island (solid) taken from Fig. 4, and 7-year running means of annual tropical Pacific SST anomalies (dash) relative to a 1951–1980 mean. The SST anomalies have been multiplied by minus one.

location at Chatham Island, the low-frequency variations in both curves are suggestive of a relationship between tropical SST fluctuations and changes in the SAO and the circumpolar trough. In another study, Meehl and Albrecht (1988) noted that an improved convective scheme in the NCAR Community Climate Model (CCM) warmed the model troposphere, especially in the tropics, which increased the equator-to-pole temperature gradient. As a consequence, the midlatitude zonal wind maximum was stronger in the CCM, and they also observed that the SLP was lower at high southern latitudes in the circumpolar trough surrounding Antarctica.

Recently, there have also been attempts to relate tropical SST changes to the variability of SH planetary wave activity and stratospheric circulations, including variations in the distribution of total ozone over Antarctica. Tropospheric forcing is important in determining both the mean state and the disturbance structure of the stratosphere. The possible influence of planetary wave activity on the interannual variability of ozone has been discussed by Mahlman and Fels (1986) and Dunkerton (1988) among others. Newman and Randel (1988) show that large observed interannual variations in the SH spring stratospheric temperatures and ozone levels are highly correlated with similar variability of planetary wave forcing from the troposphere. They also document a notable decrease of lower stratospheric wave driving over the period 1979–1986 (see also Nagatani and Miller (1987)) consistent with observed trends of temperature and ozone. A more recent investigation by Kawahira and Hirooka (1992) showed that stationary wave 1 (which dominates the SH spring stratospheric eddy fluxes, e.g., Newman and Randel, 1988; Randel, 1992) was considerably weaker in the 1980s than in the early 1970s, and Shiotani et al. (1993) showed that the interannual variability of the stratospheric wave-1 activity during the 1980s could be related to dynamical forcings from the troposphere. The relationship between these variations in the planetary wave structure of the SH and SST fluctuations in the tropics was established by Kodera and Yamazaki (1989). Similarly, Komhyr et al. (1991) related the higher SSTs of the 1980s to changes in SH extratropical planetary wave activity, and they also demonstrated that a significant negative correlation exists between October ozone values over the South Pole and June–August SSTs in the eastern equatorial Pacific.

The aforementioned studies indicate that changes in the vortex of the lower stratosphere in spring during the 1980s are probably related to concurrent changes in the tropospheric circulation of the SH, and they may be related to the heat content of tropical surface waters. Through the influence of vertically propagating waves, it is well established that the stratosphere will respond to changes in the tropospheric circulation. It is less obvious, however, how the troposphere might respond to changes in the stratospheric circulation. The tropospheric response to stratospheric changes has primarily been examined for the Northern Hemisphere (NH) during winter when the wave forcing is strong. For example, Boville (1984) used an atmospheric general circulation model to experimentally increase the strength of the stratospheric polar night jet compared to a control simulation. He found that differences between the two runs were not limited to the stratosphere, but substantial changes were also found in the structure of the NH tropospheric stationary waves. In another modeling study, Kodera et al. (1991) demonstrated that anomalies in the strength of the NH winter polar night jet can propagate into the troposphere through wave-mean flow interactions. A similar study to examine the tropospheric response to changes in the SH winter stratosphere, such as those resulting from the observed decline of ozone levels over Antarctica, could help determine the causes of the circulation changes observed during the 1980s.

Nevertheless, it is clear that the one month extension of the strength of the circumpolar trough and the polar vortex in the troposphere and lower stratosphere from September/October to November/December has dynamical implications for the stratospheric vortex and ozone chemistry. A continued strong polar vortex into late spring is consistent with the decreases in the planetary wave activity and in the transports of ozone, heat, and momentum during the 1980s found in many of the aforementioned studies. A consequence is prolonged lower temperatures in the Antarctic polar vortex, which are related to ozone destruction by heterogeneous chemical processes. The result would be a positive feedback where the low temperatures are then prolonged radiatively, and the changes in radiative heating would further delay the final spring warming. Thus, the significant changes in the troposphere and lower stratosphere between the 1970s and the 1980s described in this study emphasize that variations in Antarctic ozone amounts require an integrated consideration of chemical, radiative and dynamical processes.

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