Interannual variability associated with Semiannual Oscillation in southern high latitudes

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[1] The annual and interannual variations of sea level pressure (SLP) over the Southern Ocean are investigated using the NCEP/NCAR reanalysis data from 1968 to 2005. Results show that the weakening of the Semiannual Oscillation (SAO) has continued to present day but does not occur homogeneously across all longitudes. While the second harmonic of SLP has decreased over the South Pacific Ocean, its signal is still strong over the Atlantic sector up to 2005. This suggests that the mechanism influencing the amplitude of the SAO over South Atlantic Ocean is different to that in the Pacific and Indian oceans. Spectral analysis of zonally averaged SLP at 50°S and 65°S shows that significant energy is associated with the period of 4 years. The same period is found for the time series of the zonally averaged position of the circumpolar trough and for the meridional temperature gradient at 500 hPa. This interannual signal is even stronger in the time series of the SLP difference between those two latitudes: the SAO index. Wavelet analysis of the SLP time series at mid and high southern latitudes showed significant interannual energy, also with a 4 year period, at 50°S, 65°S, and in the time series of their difference. When analyzed by ocean basins, spectral analysis reveal that there is no interannual variability at the 4 year period for the Atlantic, indicating that the known weakening of the SAO is basin-dependent.


1. Introduction

[2] The atmosphere over the Southern Ocean is characterized by a circumpolar trough of low pressure around Antarctica, which shows seasonal variations in its intensity and position. It contracts and intensifies, moving southward during austral autumn and spring, while during austral winter and summer it expands northward and weakens. This twice-yearly north-south movement has been referred to in the literature as the Semiannual Oscillation (SAO). Van Loon [1967] showed that the SAO arises from the different surface heat budget in the oceanic mid and continental polar latitudes. These cause different annual cycles of temperature between the Antarctic continent and the surrounding midlatitude southern oceans, which in turn influences the meridional temperature gradient between 50°S and 65°S. More details can be obtained from Meehl [1991], who provides a substantial reexamination of the mechanisms involved in the SAO. Since the SAO results from ocean-atmosphere interaction, changes in sea surface temperature (SST) over the high-latitude oceans can modulate its variability [van den Broeke, 1998a].

[3] Interannual and longer-term variability of the SAO has been a subject of growing interest. Before the 1970s, more than 50% of the variance in SLP at mid-high latitudes was explained by the SAO. Since the late 1970s, the second harmonic of SLP at mid and high latitudes has decreased, as described in several papers [e.g., van Loon and Rogers, 1984; van Loon et al., 1993; Hurrell and van Loon, 1994; Meehl et al., 1998; van den Broeke, 1998b]. Meehl et al. [1998] have attributed this weakening to a change in the seasonal cycle of surface temperature at mid southern latitudes. The mechanisms by which these changes in temperature can propagate are not clear. However, recent changes in ENSO frequency and intensity during the last decade may have influenced the SAO. Indeed Meehl [1988] reported a relationship between ENSO and the high southern latitude circulation. Hurrell and van Loon [1994] also showed a relationship between the equatorial Pacific SST and the SAO in Chatham Island. Some other studies have examined variations in the Southern Hemisphere (SH) circulation induced by SST [Zhang et al., 1997; Garreau and Battisti, 1999; Mo, 2000], however, they do not associate the global modes of variability with changes in the SAO behavior.

[4] This work aims to investigate changes in the SAO variability from the 1970s to the present by updating the
2. Data

The study uses the 2.5° × 2.5° monthly mean SLP data from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis [Kalnay et al., 1996]. A more recent review of this data set is given by Kistler et al. [2001]. Several errors have been found in the SLP reanalysis fields, especially in their trends over the Southern Ocean and Antarctica before 1968. However, the mid and high southern regions are essential for our study, since the mean position of the circumpolar trough is located around 65°S. Because of these uncertainties, only the period after 1968 (i.e., January 1968 to December 2005) was considered, when the number of surface observations incorporated into the reanalysis increased. A long-term trend in the SLP data is removed, consistent with Hines et al. [2000], by subtracting a 10 year running mean applied to the SLP time series. The introduction of satellite data in the NCEP/NCAR reanalysis is also another point of discussions. A detailed study about these effects is given by Sturaro [2003]. According to the author the main errors occur in the tropics for layers between 700 and 50 hPa and over Southern Ocean in the layer 500 to 250 hPa, but not in sea level data or near surface. In this study we have used the reanalysis 2 (corrected) to examine the meridional temperature gradient at 500 hPa.

Harmonic analysis is used to examine the seasonal cycle of SLP as well as to characterize the mean behavior of the SAO, with special attention to the latitude band between 50°S and 65°S.

In order to examine the interannual variability of the SAO, the seasonal means for the entire record was removed to define the anomaly time series. A power spectrum analysis was done by implementing the SSA-MTM Toolkit (Singular-Spectrum Analysis-Multi-Taper Method), described by Ghil [1997]. The MTM technique attempts to reduce the variance of spectral estimates by multiplying the time series by a small set of orthogonal window functions rather than the unique data taper. The result is a set of independent spectral estimates that provides a final spectrum based on the ensemble average. Detailed description of the MTM is given by Percival and Walden [1993].

We also used wavelet analysis in order to decompose the anomaly time series into time-frequency space simultaneously, following Torrence and Compo [1998]. The main advantage of wavelet analysis is that it can extract the amplitude of any “periodic” signals within the series as well as show how this amplitude varies with time. In other words, this method can analyze time series with nonstationary power at many different frequencies. We use the Morlet wavelet, which is a complex exponential modulated by a Gaussian, \( \exp^{i\omega_0t} \exp^{-\frac{t^2}{2\sigma^2}} \), where \( t \) is the time, \( s \) is the wavelet scale, and \( \omega_0 \) is a nondimensional frequency taken to be 6 to satisfy the admissibility condition (zero mean and energy localized in both time and frequency space). To test the significance of peaks, a background Fourier spectrum was chosen as described by Torrence and Compo [1998].

3. Results

3.1. Sea Level Pressure and the Semiannual Oscillation

Figure 1a shows the latitude versus time evolution of the second harmonic of the monthly mean, zonally averaged SLP for each year. Van Loon et al. [1993] used the SLP data set from the Australian Bureau of Meteorology covering the period of 1974 to 1988 to create a similar diagram. Here, we have expanded their analysis by including the later 18 years and the earlier 6 years of SLP data based on the NCEP/NCAR reanalysis. Simmonds and Jones [1998] also show a similar figure using the same data set for the period of 1973 to 1993. However, unlike these previous studies, we will discuss the SAO variability not only in terms of the zonally averaged SLP but also in relation to each oceanic basin. Figure 1a reveals that the zonal mean amplitudes are higher in the southern latitudes, reaching 5 hPa at approximately 67°S in 1975 and 1982, while at 50°S the amplitudes range between 1 and 3 hPa. The second harmonic is more important (explains more variance) than the first one (not shown) across 45°S and 65°S (see shaded areas of Figure 1a), because of the half-yearly changes in depth and location of the circumpolar trough. Across 65°S, the second harmonic is approximately 24% more important than the first one, explaining variance as high as 70% for some periods [1971, 1975–1976, 1982, 1984, 1997 and 2005]. An important characteristic of Figure 1a is the amplitude minimum located between 55°S and 60°S where the phase reverses. The out-of-phase annual cycles for SLP at 50°S and 65°S, that can be seen in Figures 1b and 1c (thick solid line) respectively, is consistent with this behavior. Figure 1a shows the weakening of the second harmonic beginning in the early 1980s and continuing until recently, which agrees with previous studies of van Loon et al. [1993], Hurrell and van Loon [1994] and Simmonds and Jones [1998]. Nevertheless, the SAO feature seems to intensify in 2005, when the amplitude of the second harmonic at 65°S reaches 4 hPa and explains more than 60% of the total variance. It should be noted that the extension of the data record does not change the findings of the mentioned studies but updates previous studies and permits a better basin-dependence analysis.

Variability from one decade to the next can be seen in the annual cycle of the zonally averaged SLP at 50°S (Figure 1c) for 1968–1978 (dashed line), 1979–1990 (dotted-dashed line) and 1991–2005 (solid line) with respect to the mean for the entire period (thick solid line). The SLP cycle at 65°S (Figure 1b) does not weaken significantly during the whole period. The decrease of the second harmonic is evident at 50°S (Figure 1c) but not at 65°S (Figure 1b). During the first decadal period (1968–1978, dashed line), the annual cycle at 50°S shows a strong SAO. The following decades show a reduction in the amplitude of the zonally averaged SLP in spring and consequently a weakening of the second harmonic. The changes at 50°S occur mainly during the austral spring (September-October-November), indicating that the ocean-atmosphere coupling is present in late summer/early fall but not in spring. It should be noted that the annual cycle of the SLP (Figure 1c)
has energy in the third harmonic (not shown) for the 1979–1990 period because of the appearance of two maxima, one in August and another in November. The decadal weakening in SLP shown here is consistent with the previous results of Hurrell and van Loon [1994] and Simmonds and Jones [1998].

[11] The annual cycle of the SLP difference between 65°S and 50°S can be seen in Figure 1d. This difference was first used by van Loon [1967] as an index of the SAO intensity. Because of the time lag between the annual cycles in SLP at mid and high southern latitudes, a significant difference is found in March and October (thick solid line), of approximately −19.5 hPa. Given the weak fluctuation at 50°S, the SAO index in Figure 1d is driven more by the activity at 65°S than that at 50°S. However, it does not mean that SLP at 50°S is not important in SAO. On the contrary, according to van Loon [1967] the SAO mechanism is due to the differing heat budget over Antarctic continent and midlatitude oceans, and thus SLP at 50°S is essential to modulate the second harmonic in the meridional pressure gradient. Meehl et al. [1998] attributed the SAO weakening to a change in surface and 500 hPa temperature gradient between 50°S and 65°S.

[12] Figure 1d reveals a peak in September in SAO index during the 1990s. This peak is also seen for the SLP annual cycle at 65°S (Figure 1b). Meehl et al. [1998] found a shift of the second SLP peak (that is not seen here) due to a one month delay in the lowest pressure at 70°S. Note that the difference seen between Figures 1b and 1d here and the Figure 2 from Meehl et al. [1998] can be attributed to differences in the period and latitude considered here. While we used 1968 to 1978 for the first decade, Meehl et al. [1998] used the period of 1972–1979, which suggests that the early 1970s were important to define the SLP minimum in September at 70°S. Moreover, Meehl et al. [1998] used SLP at 70°S instead of 65°S, which is the latitude considered for this study.

[13] The changes in the second harmonic do not occur homogeneously at all longitudes. The amplitude and variance of the second harmonic over the Southern Ocean for the different decades makes it clear that before 1978 (Figure 2a) the second harmonic was very prominent over the three oceanic basins at midlatitudes and around the Antarctic continent. The period between 1979 and 1990 (Figure 2b) was characterized by a significant reduction of the SAO signal at the mid southern latitudes and around the Antarc...
Figure 2. Amplitude of the second harmonic for three periods: (a) 1968–1978, (b) 1979–1990, and (c) 1991–2005. Shaded areas indicate values greater than 40% of the explained variance. Contour intervals are 0.5 hPa and 20%, respectively.

Figure 3. Annual cycle of SLP at 50°S for the three averaged oceanic regions: (a) Pacific (180–225°W), (b) Atlantic (55°W–0°E), and (c) Indian (70–110°E). Dashed line indicates 1968–1978, dash-dotted line indicates 1979–1990, and solid line indicates 1991–2005. Units are in hPa.
Antarctic Peninsula. These results are consistent with the harmonic analysis shown in Figure 1a and with van Loon and Rogers [1984] and van Loon et al. [1993]. The decrease of the second harmonic in the Antarctic Peninsula region was not big enough to reduce its magnitude in the zonal average depicted in Figure 1a. However, the most recent period (1991 to 2005, Figure 2c) shows that the second harmonic is still weak, especially in the Pacific sector. During the 1998–2005 period (not shown) the SAO shows no change relative to the 1990s mean. Although the SAO has been weakening since the late 1970s over the Pacific and Indian sectors, the same cannot be seen in the midlatitudes for the Atlantic Ocean. In fact, Figure 2c suggests that the second harmonic is still strong in the 1990s over the South Atlantic Ocean. Therefore the weakening of the SAO which began in the late 1970s has continued in the Pacific and Indian Ocean sectors but not over the South Atlantic.

[14] In order to define changes in the SAO separated by ocean basins, the annual cycle of SLP at 50°S averaged over the three oceanic regions: Pacific (180–225°W), Indian (70–110°E) and Atlantic (55°W–0°E) is examined. Figure 3 shows that the SAO is well defined over the three oceans only for the 1968–1978 period (dashed line), although the Indian sector shows the smallest second peak. The following decades shows a reduction of the amplitude of the second peak, except for the South Atlantic Ocean where the SAO remains strong (Figure 3b). The reduction in the amplitude of the SAO in the Pacific (Figure 3a) and Indian (Figure 3c) may be related to interannual-to-decadal variability in the tropics which may modulate the SAO signal in the southern extratropics. Since most of the variability over the Pacific sector is ENSO-related [Zhang et al., 1997], it could be that the SAO weakening is associated with the warm events in the equatorial Pacific Ocean. Note that unlike the other basins, ENSO-related variability is not the predominant mode of variability of the South Atlantic Ocean [Venegas et al., 1998; Wainer and Venegas, 2002; Hall and Visbeck, 2002].

[15] The second harmonic in SLP is discussed with respect to the temperature gradient at 500 mbar, as depicted in Figure 4. Examining the signal in the zonally averaged 500 hPa temperature difference between 55°S and 65°S, we note two minima: the first one occurring in March and the

![Figure 4. Annual cycle of zonally averaged meridional temperature gradient at 500 hPa between 65° and 50°S. Data are from reanalysis 2.](image)

![Figure 5. Annual cycle of meridional temperature gradient at 500 hPa between 65° and 50°S, for the three averaged oceanic regions: (a) Pacific (180–225°W), (b) Atlantic (55°W–0°E), and (c) Indian (70–110°E). Dashed line indicates 1979–1990, and solid line indicates 1991–2005. Data are from reanalysis 2. Units are in Celsius.](image)
second one in October. This meridional temperature gradient (baroclinicity) reflects the differences between heating/cooling rates at these latitudes as shown by van Loon [1967]. The changes in the temperature gradient have a significant impact on the mean position of the circumpolar trough which in turn affects pressure and wind fields.

[16] In order to find an explanation for the SAO weakening, the meridional temperature gradient was plotted in Figure 5 for the last two decades (1979–1990 and 1991–2005), considering each ocean basin separately. The Pacific sector (Figure 5a) reveals a annual cycle with different behavior between the decades. In the 1980s the gradient peak at 7.5°C in July weakens in August and has a secondary peak in September, which increases the third harmonic. Both curves indicates low baroclinity in the Pacific sector, which agrees with the SAO weakening.

[17] The Indian sector (Figure 5c) has two minima (March/April and October) more pronounced than the other two oceanic basins. The largest amplitude of the meridional temperature gradient in the Indian Ocean indicates high baroclinicity, which in turn should be related to a strong SAO signal. Even though the Indian Ocean shows a strong meridional temperature gradient, with two maxima amplitude in austral autumn and spring, the SAO index is not strong over this region. This contradiction was discussed by Walland and Simmonds [1999] who considered not only the

\[\text{Figure 6. Time series of SLP anomalies at (a) 50}^\circ\text{S and (b) 65}^\circ\text{S. Bold line indicates 1-year running mean. Units are in hPa.}\]
baroclinicity but also the static stability of atmosphere. They showed that the static stability plays an essential role in determining the second harmonic in SLP. It may be that the SAO decrease in Indian sector is due to an increase of the static stability. The reason why the static stability has changed during the last decades in Indian sector is the point that must be addressed.

The annual cycle of the meridional temperature gradient of the Atlantic (Figure 5b) is less pronounced than that of the Pacific and Indian oceans. Once more the static stability of atmosphere seems to play an important role in modulating the second harmonic of SLP in this region, considering that the SAO signal is still strong in the present days over the Atlantic Ocean.

3.2. Variability of the SAO

Figure 6 depicts the SLP anomalies at 50°S and 65°S. It shows a low-frequency variability that is better seen in the one-year smoothed time series (bold line). To uncover the interannual variability of SAO signal, MTM spectral analysis was computed (Figure 7) for the time series of the anomalies at 50°S and 65°S. Both time series show a spectral peak at approximately 4 years (around 0.02 cycles/month), statistically significant at 95% with a lag of approximately 5 months between the peak for 50°S and 65°S. The MTM spectra for the SAO index (SLP difference between 50°S and 65°S, Figure 7c), reveals a very pronounced harmonic peak at 4 years (around 0.021 cycles/month), surprisingly stronger than for the individual latitudes (i.e., Figures 7a and 7b), suggesting that the phase difference between 50°S and 65°S varies on the interannual timescales.

Since the contraction (expansion) and deepening (weakening) of the circumpolar trough (CPT) is a fundamental feature of the SAO and has a direct effect on the SAO index, spectral analysis was applied to the anomalies time series of the circumpolar trough position (solid black line on Figure 2) to determine if it showed similar variability. The position of the circumpolar trough (Figure 7d) also shows a 4-year peak. Considering that both ENSO and the Indian Monsoon could affect variability of the circumpolar trough [Meehl, 1991] it may be that ENSO influences the SAO through the circumpolar trough. Actually, it is known that this 4-year period is one of the predominant frequencies of ENSO variability. Indeed, MTM spectral analysis done for the SAO index for the global zonal average and for each individual basin (Figure 8) shows that the 4 year (interannual) peak is prominent for the Indian Ocean (Figure 8c), and
present for the Pacific Ocean (Figure 8b) but does not reach the 99% level of significance for the Atlantic (Figure 8d).

Figure 9 depicts the MTM spectral analysis for the zonally averaged meridional temperature gradient between 65°S and 50°S and for each oceanic basin. The 4-year variability is significant at 95% level in the zonally averaged temperature gradient (0.0195 cycles/month). In the Pacific and Atlantic oceans (Figures 9b and 9c, respectively) a peak at approximately 5.3 years is present. In the Indian sector (Figure 9d) as well as in the Atlantic (Figure 9c) there is a small peak associated with the variability of 2.5 years. All power spectra from Figure 9 shows energy at 1.5 year (0.056 cycles/month). This high-frequency variability can be associated with the Southern Annular Mode (SAM), studied by Thompson and Wallace [2000]. The SAM can be described as a zonally symmetric structure in SLP that oscillates between high and middle southern latitudes. Thompson et al. [2000] have documented a drift in recent decades toward the high index polarity of the SAM. One may argue that this trend could be a possible mechanism to explain the SAO decrease, since SAM is directly related to SLP at 65°S. However, as SAM has a very deep zonal structure it is expected to affect equally all the three oceanic basins and not only the Pacific and Indian sectors. Furthermore, the SAO feature is more likely related to a zonal wavenumber three pattern (Figure 2a) than a zonally symmetric structure. Moreover, Burnett and McNicoll [2000] suggested that SAO weakening was linked to a deepening of the circum-polar low-pressure trough and an intensification of mid-latitude ridging, that would produce a contraction of the vortex in mid-latitudes, an expansion of the vortex in polar regions, and a larger meridional height gradient, all observed in 500-hPa vortex records.

To measure the variance of the time series of zonally averaged SLP at each scale (period) and at each time as well as to validate the MTM spectral results, wavelet analysis (Figure 10) was performed on SLP at 50°S and 65°S. The bold contour encloses regions of greater than 95% confidence for a red noise process. The wavelet power spectrum (Figure 10a) for the zonally averaged SLP anomalies time series at 50°S, shows energies at 1–2 years, and also at 4 years, being significant at 95% level from 1963 to 1969 and 1974 to 1982. The energy in the 2–4 year period decreased after 1982. The SLP at 65°S, shown in Figure 10b, reveals high variance from 1974 to 1982 and 1990 to 1999 associated with a 4 year period. There is also significant energy at 1–2 years along the time series (Figure 10b). The time series of the difference between the SLP at 65°S and 50°S, also shows significant energy at 4 year period of variability, particularly from 1960 to 1971 and 1977 to 1983 (Figure 10c). The 4 year period found in Figures 10a–10c is consistent with the MTM results. To clarify changes in the SAO at 50°S, at times series of September-October-November (SON) was examined. This period was chosen since the largest changes in the SLP second harmonic occurs during the austral spring. Figure 10d shows the wavelet power spectrum of the zonally averaged SLP during SON. It reveals a lower-frequency, high-energy signal from 1965 to 1992 associated
with a 6–10 year period. One may argue that this low frequency could be associated with the Antarctic Circumpolar Wave (ACW) defined by White and Peterson [1996] and lately linked to ENSO [Peterson and White, 1998]. The ACW is a coupled phenomenon in the southern mid and high latitudes, characterized by an eastward propagating signal in the ocean, atmosphere and sea ice in a wavenumber 2 pattern, thus requiring 8–10 years to circle the globe. More recently, Peterson and White [1998] showed that interannual anomalies in SST, SLP and precipitable water are linked with the ENSO cycle at the equator through a slow oceanic teleconnection. The extent to which this is true is still subject of discussions. We note that the classic ACW signal cannot be seen prior to 1981, which is the period when the SAO started to decrease. Because of that, there is an interesting possibility that the ACW is out-of-phase related to the SAO variability. In the late 1990s the SAO seems to recover (at least in the Atlantic sector) and the ACW is much less clearly identifiable. Simmonds [2003] also suggested the relationship between the ACW and the SAO variability.

4. Discussion and Conclusions

The SAO in SLP was examined using NCEP/NCAR reanalysis data set from 1968 to 2005. This study expands the previous findings of van Loon and Rogers [1984], van Loon et al. [1993] and Hurrell and van Loon [1994], among others, by not only extending the analysis of the SAO behavior over the last decade but most importantly, by examining the SAO variability over the three oceanic basins separately.

Investigation into the weakening of the SAO to the present day is essential to improve our knowledge about the mechanisms responsible for its amplitude modulation in the Southern Hemisphere. A continuous decrease of the second harmonic in the zonally averaged SLP can be seen. This weakening is not homogeneously distributed across all longitudes rather it is pronounced over the midlatitudes of the Pacific and Indian oceans. The SAO signal is evident and clear at midlatitudes over the Atlantic sector during the last decade, unlike what is happening over the other oceanic basins.

One might argue that the introduction of satellite data in the NCEP/NCAR reanalysis in the late 1970s may have an effect in the weakening of the SAO. However, many previous studies have reported the SAO decrease by using other data sets, particularly, van Loon et al. [1993] and Simmonds and Jones [1998] who detected the SAO weakening after the 1980s using a long series of data from observational stations included in Australian Bureau
of Meteorology. If the SAO weakening was an artificial result of the satellite introduction in reanalysis, one would not expect to find different behavior among the oceanic basins.

Special attention was given to the signal in the 500 hPa temperature difference between 55°S and 65°S, during austral spring (September-October-November). This temperature gradient reflects the differences between heating/cooling rates at these latitudes as shown by van...
The changes in the temperature gradient have a significant impact on the mean position of the circumpolar trough, which in turn affects the pressure and wind fields. An important issue raised in this study is the fact that the meridional temperature gradient (baroclinicity) is not the only cause for determining the structure of the SAO, but the static stability has also to be taken into account. Walland and Simmonds [1999] pointed out that when the static stability is considered the maximum baroclinicity occurs in September/October, modulating the amplitude of the twice-annual maxima in SLP. In other words, the static stability in austral spring is weak enough to lead a larger baroclinic response for a given horizontal temperature gradient. In austral autumn, on the other hand, even though the horizontal temperature gradients are larger, the higher static stability ensures that the baroclinic response is weaker. Regarding this statement, one may argue that the SAO is still intense over the South Atlantic because the atmosphere over this oceanic basin is unstable enough to maintain the second harmonic strong in SLP. Following the same argument, the static stability in spring over the Pacific and Indian oceans might be higher than that in the Atlantic, resulting in a weaker baroclinic response, which in turn, decreases the SAO signal. This hypothesis may generate new studies in terms of baroclinity and static stability. Another mechanism that can be linked to the SAO variability is the ENSO. Since both Pacific and Indian basins are strongly modulated by ENSO variability unlike the South Atlantic (e.g., Figure 8), it is hypothesized that interannual variability would be an integral part of the SAO variability over the ocean basins. Results for the MTM spectral analysis and wavelet power spectrum indeed show significant interannual variability of the (1) SLP time series at 50°S and 65°S, (2) their difference; (3) the zonally averaged mean position of the circumpolar trough, and (4) in the meridional temperature gradient, all associated with a period of 4 years. By contrast, the zonally averaged SLP anomalies time series of September-October-November at 50°S shows very high variance from 1965 to 1992 associated with the 6–10 year period. The results obtained in this study provide a basis for investigating a possible relationship between ENSO and SAO variability. Warm events can change the oceanic heat processes responsible for the occurrence of the SAO at midlatitudes in the Pacific and Indian oceans. Further investigation is underway to explore these physical mechanisms and to understand better why the South Atlantic does not respond in the same way.


