J3.3 DECADAL VARIABILITY OF THE ENSO TELECONNECTION TO THE SOUTH PACIFIC GOVERNED BY COUPLING WITH THE ANTARCTIC OSCILLATION

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1. Introduction

The tropics are an area of high variability on interannual and interdecadal time scales. The El Niño-Southern Oscillation (ENSO), which is associated with the cycle of above normal sea surface temperatures (SSTs) in the central and eastern equatorial Pacific and enhanced convection associated with these SST anomalies, has impacts that affect global climate on interannual and interdecadal timescales (e.g., Karoly et al. 1996). One area where the ENSO teleconnection appears particularly strong in the high southern latitudes is in the South Pacific Ocean, off the coast of Antarctica and in the vicinity of the Drake Passage (see Turner 2004 and references therein).

In the southeast Pacific, a large blocking high pressure forms as a response during El Niño, i.e., ENSO warm events (Renwick and Revell 1999; Renwick 1998; van Loon and Shea 1987). The low-frequency variability is readily seen in the amplitude of this pressure center, which is part of the Pacific South American Pattern (PSA, Mo and Ghil 1987). Similar to its counterpart in the Northern Hemisphere, the Pacific North American Pattern (PNA, Wallace and Gutzler 1981), the PSA represents a series of alternating positive and negative geopotential height anomalies extending from the west-central equatorial Pacific through Australia / New Zealand, to the South Pacific near Antarctica / South America, and then bending northward toward Africa. The PSA has been shown to be induced by tropical forcing (Revell et al. 2001), and is thus related to ENSO.

There is a definite need to better understand the decadal variability of the ENSO signal in high southern latitudes. Results from Cullather et al. (1996) and Bromwich et al. (2000) indicate a strong shift in the correlation between West Antarctic (180°-120°W) precipitation minus evaporation (P-E) and the SOI using atmospheric reanalysis and operational analysis over the last two decades. The time series of P-E was positively correlated with the SOI until about 1990, after which it became strongly anticorrelated, a relationship that existed through at least 2000. Further, Genthon et al. (2003) note variability in the correlation between the SOI and the 500 hPa geopotential height field in the southeast Pacific from the 1980s and the 1990s using reanalysis and model output. Recently, Bromwich et al. (2004) identify significant shifts in the position of convection and the associated amplification of the PSA wave-train in DJF in the late 1990s El Niño / La Niña difference vs. the difference between all other El Niños and La Niñas from 1979-2000. Thus, there appears to be strong decadal variability of the ENSO signal in the South Pacific; however, the mechanisms forcing the variability remain undetermined.

This study examines the ENSO teleconnection to the South Pacific / Drake Passage region on decadal time scales in an attempt to determine the mechanism leading to the low-frequency variability. Section 2 describes the data and methodology used in the study. The decadal variability of the ENSO teleconnection is examined in Section 3 using both reanalysis data and observations. Section 4 details the mechanisms responsible for the decadal variability seen in Section 3. A discussion is presented in Section 5, and a summary is offered in Section 6.

2. Data and Methods

Monthly mean 500 hPa geopotential height data are provided by the European Centre for Medium-Range Weather Forecasts 40-year Reanalysis (ERA-40). Data from the 2.5 by 2.5 degree latitude-longitude grid were used for the time period of 1970 to 2001, and were obtained from the ECMWF data server (http://data.ecmwf.int/data/). ERA-40 has been proven to have many shortcomings in high southern latitudes (Bromwich and Fogt 2004) that limit its applicability before 1970. However, ERA-40 is chosen here due to its superior performance in the modern satellite era over the National Centers for Environmental Predication / National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Bromwich and Fogt 2004).

The Southern Oscillation Index (SOI) obtained from the Climate Analysis Section of the Australian Bureau of Meteorology's National Climate Centre is used to monitor the effects of ENSO. The SOI is the difference between the pressures at Tahiti (17.5°S, 149.6°W) and Darwin, Australia (12.4°S, 130.9°E). This particular SOI is standardized by the Troup (1965) method, with values multiplied by 10 so that they may be represented as a whole number.

Spatial correlation analysis is used to demonstrate the ENSO teleconnections across the Southern Hemisphere. Significance levels of the correlation values were determined using a two-tailed Students' t test, with 8 degrees of freedom per decade since the seasonal mean time series do not show any autocorrelation (and are thus assumed independent). With 8 degrees of freedom, correlations >0.76 are

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significant at the 99% level, >0.63 at the 95% level, and >0.55 at the 90% level. Regression analysis is also used as another method to show linear dependence and tropical to high latitude teleconnections.

Principal Components Analysis was employed using seasonal anomalies of the ERA-40 500 hPa geopotential height fields from 1970-2001. Seasonal anomalies, defined as the individual seasonal average minus the seasonal grand mean for the 32 years, were interpolated to a 31 x 31 Cartesian grid centered over the South Pole with spacing of 450 km. Thus the domain has edges at about 12.5°S at the corners, and around 30°S at the midpoints of each side so that subtropical connections can be made. Principal components (PCs) were constructed using the covariance matrix, and Varimax rotation was performed on the PCs and used throughout the analysis; rotation of principal components is encouraged (Richman 1986; Trenberth et al. 2004). For the seasonal PCs, 4 factors were retained for the Varimax rotation. Four factors were chosen since the first 4 modes explained over 60% of the total variance and the remaining modes explained less than 5% each; the scree plot (not shown) becomes fairly linear after the 5th eigenvalue.

3. Decadal Variability of the ENSO Teleconnection

To view the seasonal cycle, seasonal correlations are calculated between the ERA-40 500 hPa geopotential heights and the SOI. Through the four seasons the correlation values change substantially and the annual mean plots are highly dominated by the SON (Fig. 1) and DJF (not shown) correlations, the peak seasons of ENSO. Figure 1 shows substantial variability between the decades. Notably, the 1970s and the 1990s demonstrate a statistically significant teleconnection, especially the latter, where the values are significant at >99%. The teleconnection in the 1980s (Fig. 1b), however, is weak and more zonally elongated than other decades, suggesting a disruption in the circulation or in the propagation of the tropical signal to the high southern latitudes during austral spring.

In SON, large changes occur between the 1980s and the 1990s, from essentially no significant correlation in the 1980s to a large area significant at >99% level in the 1990s. In DJF, however, the changes between the 1980s and the 1990s are much less marked. Both decades in the summer show a significant correlation to the South Pacific, although the teleconnection has a slightly different spatial representation. Since the teleconnection is insignificant in MAM and JJA, and largely maintained between the 1980s and the 1990s in DJF, the differences noted between the annual mean teleconnection patterns for the 1980s and the 1990s (Genthon et al. 2003, Bromwich et al. 2000) can primarily be explained by the substantial differences in SON between the 1980s and the 1990s.

4. Mechanisms leading to decadal variability

4.1 Southern Hemisphere circulation patterns

In the high southern latitudes, the dominant mode of the annual mean circulation variability is the southern annular mode (SAM), which has also been referred to as the Antarctic Oscillation (AAO, Thompson and Wallace 2000; Gong and Wang 1999). Represented as the first Empirical Orthogonal Function (EOF) in the month-to-month 500 hPa geopotential heights (i.e., Rogers and van Loon 1982; Kiladis and Mo 1998) as well as SLP (Rogers and van Loon 1982; Gong and Wang 1999), the AAO is characterized by zonal pressure anomalies in the mid-latitudes having the opposite sign to the zonal pressure anomalies over Antarctica and the high southern latitudes.

A previous study by Mo and Higgins (1998) shows the linkage between the tropical convection and the PSA modes. They identify two PSA modes in the SH winter, PSA1 and PSA2, using both the NCEP / NCAR and the NASA Data Assimilation Office reanalyses. The PSA1 mode is associated with enhanced convection in the Pacific between 140°E and 170°W and suppressed convection over the Indian Ocean. Spatially, their PSA1 mode appears as a large center in the South Pacific Ocean. The PSA2 mode is forced by positive convective anomalies in the central Pacific from 160°E to 150°W just south of the equator and suppressed convection over the western Pacific and appears as a wave-three pattern in the high southern latitudes. The PSA mode associated with each ENSO event is largely governed by the position of the tropical convection.

To examine the dominant modes of circulation during SON, when the most marked decadal variability is observed, PCA is performed using the SON seasonal anomalies for 1970-2001. PCA results obtained using monthly anomalies (not shown) are representative of previous results (i.e., Kiladis and Mo 1998, Mo 2000), giving confidence to the results displayed here using seasonal anomalies. There are notable differences in the seasonal PCA results for SON, however. After rotation, the wave-3 pattern associated with ENSO (the PSA2 pattern) appears as the leading mode, with the PSA1 pattern depicted as the second mode, and the AAO pattern as the third mode. Although this may seem surprising that the PSA2 pattern leads the rotated patterns, it is physically plausible. Mo (2000) details how the PSA2 pattern is strongly forced by OLR anomalies not only in the central Pacific but also in the western Pacific along Indonesia. During the austral spring, SST anomalies along Indonesia are at their maximum. This is especially the case during this time period (1970-2001) as there are several events during the 1970s and the 1990s when these SST anomalies, characterized by the Indian Ocean Dipole (Saji et al. 1999), are very strong.

Figure 2a presents the time series extracted from the RPCs along with the seasonally averaged SOI during SON. Figure 2b presents the ERA-40 constructed AAOI for SON based on the definition in Gong and Wang (1999):

$$AAOI = MSLP_{40S} - MSLP_{65S}$$

where the MSLP represents the zonally averaged

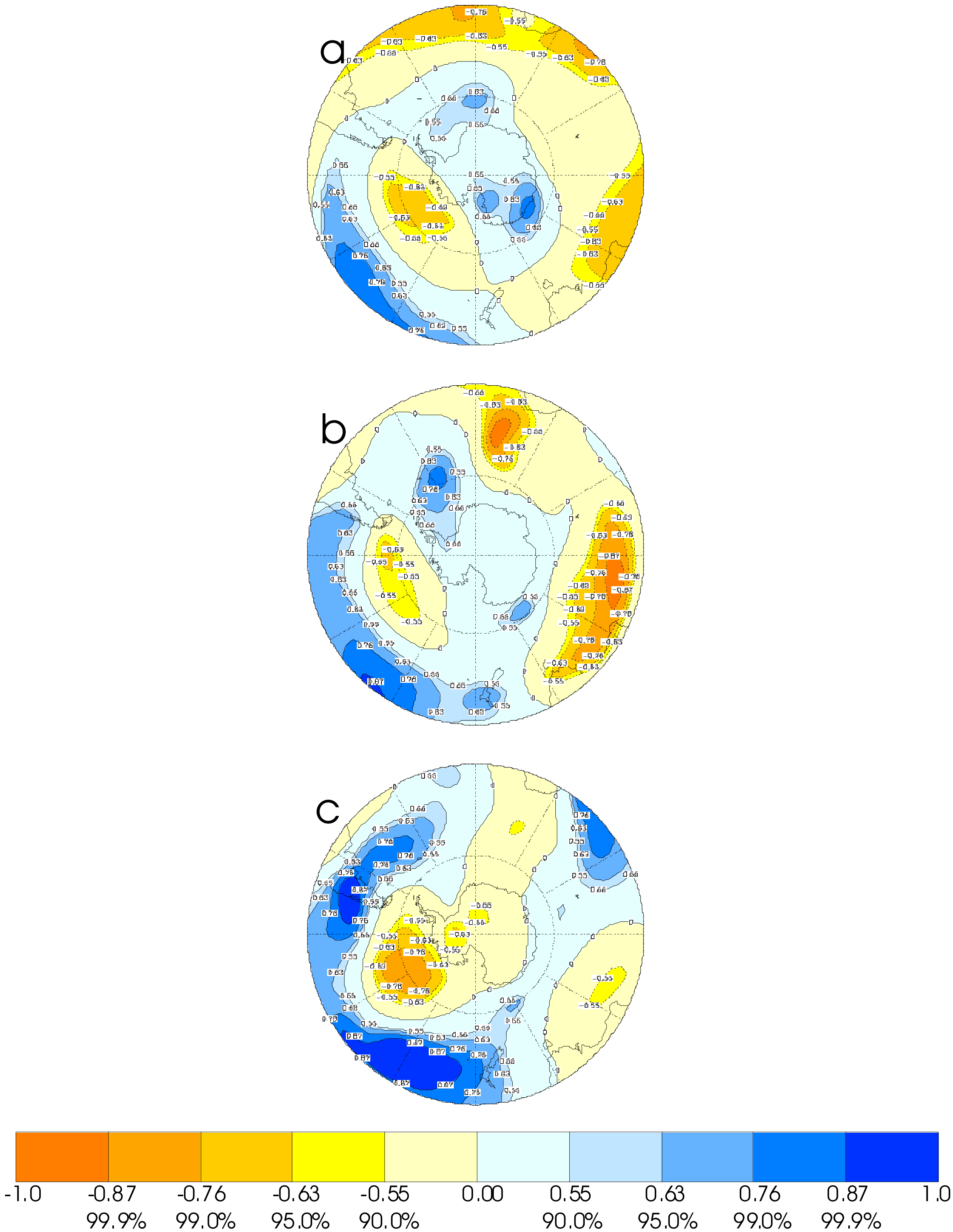

Figure 1. ERA-40 SON 500 hPa geopotential height correlations with the SOI for a) 1970s b) 1980s c) 1990s. Significance levels are listed below the key.

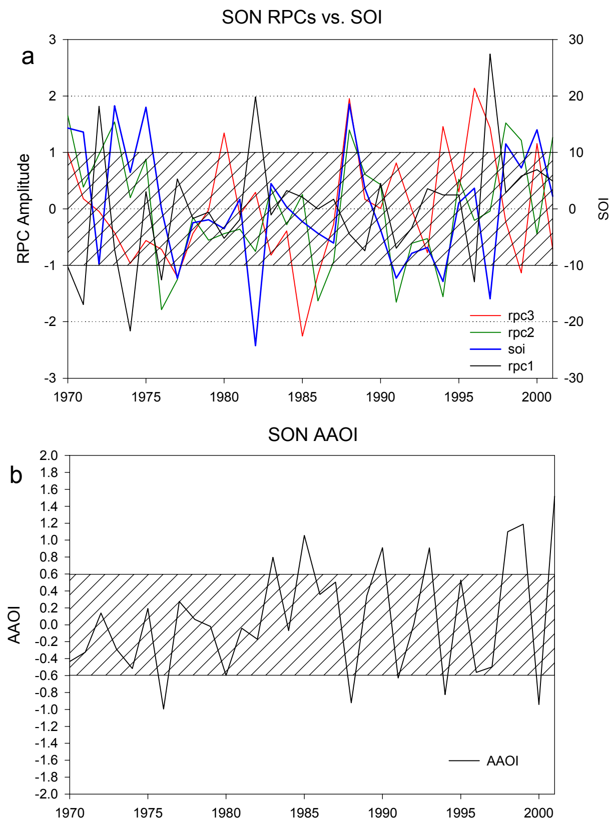

Figure 2. a) Time series of the SON RPCs vs. the SOI (blue dotted line). b) Time series of the SON AAOI constructed from the ERA-40 data set.

Year	Type	RPCs associated (if any)	sign of AAOI (if significant)
1970	LN	+RPC2 -RPC1	
1971	LN	-RPC1	
1973	LN	+RPC2	
1975	LN	none	
1977	EN	-RPC2 -RPC3	
1982	EN	+RPC1	
1988	LN	+RPC3 +RPC2	negative
1991	EN	-RPC2	negative
1994	EN	-RPC2 +RPC3	negative
1997	EN	+RPC1 +RPC3	
1998	LN	+RPC2	positive

Table 1. Significant (exceeding ± one standard deviation) ENSO (EN= El Niño, LN = La Niña) events during SON from 1970-1999, obtained by inspection from Fig. 2. Significant (exceeding ± one standard deviation) RPCs co-occurring with the ENSO events are listed to emphasize the ENSO response in the Southern Hemisphere circulation. Also listed is the sign of the AAOI, if significant.

standardized MSLP at the given latitude belt. To determine periods of significant RPCs co-occurring with significant SOI (AAOI) events, values less than one standard deviation from the mean are shaded with a semi-transparent box. Table 1 depicts the significant ENSO events (events having an SOI of ±10hPa) and the corresponding (if any) significant RPCs obtained from inspection of Fig. 2a; the sign of the AAOI, if significant, is listed as well, obtained from Fig. 2b. Table 1 clearly demonstrates that in the majority of strong ENSO events (defined EN for El Niño and LN for La Niña) there is a strong association of the RPC2 mode (the PSA1 pattern), in agreement with previous literature (Karoly 1989, Mo and Higgins 1998, Mo 2000). However, the RPC2 mode is not often solely associated with the ENSO forcing, as indicated here. The sole RPC2 response is more common in the 1990s (Table 1 and Fig. 2), where half of the ENSO events respond with a pure RPC2 pattern. The RPC1 / PSA2 pattern also often forms as a response to the ENSO forcing (Table 1). This is readily observed in the two strongest El Niño events over the last three decades in 1982 and 1997, especially the latter as this event produces a statistically strong (+ three standard deviations) RPC1 pattern (Fig. 2).

The AAOI has significant values in four of the last five ENSO events (Fig. 2b and Table 1). Of these, the AAOI is generally negative for an EN (SOI <0) and positive for a LN (SOI >0), although the 1988 LN event does not conform to this positive correlation. As seen with the SOI, the RPC3 pattern associated with the AAO does not always appear every time the AAOI is significant (as in 1991); it can also appear when the AAOI is not significant (as in 1997). The factors causing the anticorrelation between the AAOI and SOI during the 1988 LN warrant further investigation.

4.2 ENSO and AAO interactions in SON

To examine the AAO / ENSO coupling further, the SON sea surface temperature (SST) anomalies between 45°S and 45°N were regressed on the SON AAOI anomaly time series in a manner similar to Mo (2000). The SST data were obtained from the National Oceanic and Atmospheric Administration (NOAA) extended reconstructed Reynold's SST data set made available by the Climate Diagnostic Center (CDC, http://www.cdc.noaa.gov/cdc/data.noaa.ersst.html). The results are displayed in Fig. 3a for the whole time series and for the three decades individually (Fig. 3b-d). As expected, the overall results (Fig. 3a) are similar to Mo (2000), showing a weak linkage to the central Pacific SSTs. However, her finding showing significant connections to the tropical SSTs is biased by the later decades, especially the 1990s. During the 1970s and the 1980s (Figs. 3b,c), the AAO shows essentially no relationship to the central Pacific SST anomalies. The 1990s (Fig. 3d), however, are much different in that there is a strong and significant relationship (>95% level) between the AAOI and the central Pacific SST anomalies unlike that seen in the previous two decades. Interestingly, the regression coefficients in Fig. 3d are spatially arranged in a fashion similar to the SSTs anomalies seen during an El Niño event. This finding is robust since it is not biased by any significant trend in the AAOI during SON (c.f. Fig. 2b) and since the standard error in each regression is small. The coupling found between the AAOI and the Pacific SSTs is also found in

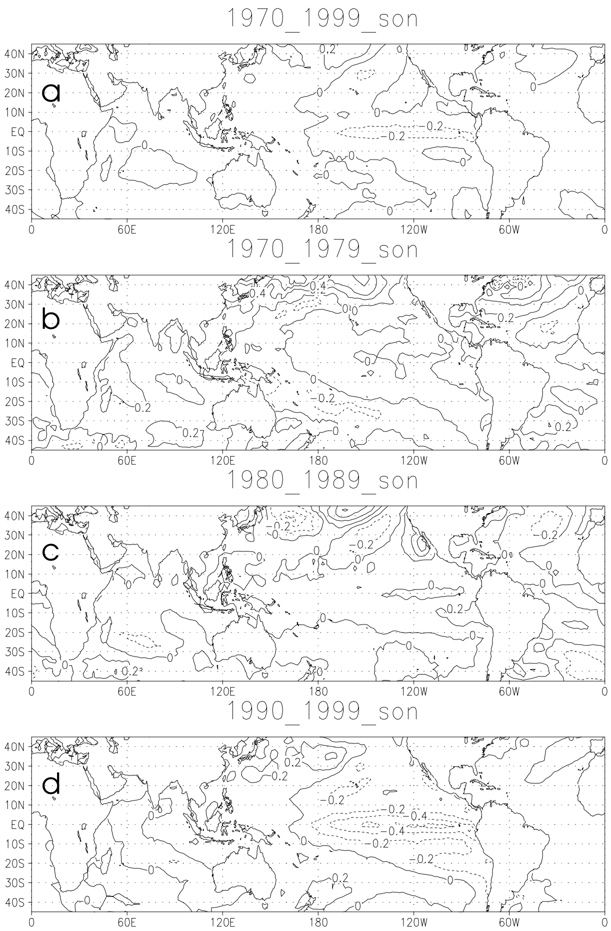

Figure 3. SON SST anomalies from 45°S to 45°N for SON AAOI anomalies regressed upon a) 1970 to 1999 b) 1970 to 1979 c) 1980 to 1989 d) 1990 to 1999. Contour interval is 0.2 °C / unit AAOI.

the atmospheric time series. The correlation coefficient between the SON AAOI and the SOI is only significant (>95% level) in the 1990s (0.71), in complete agreement with the magnitude of the ENSO teleconnection presented in Fig. 1.

The relationship between the SOI and the AAOI is also examined using a scatter plot of the SOI vs. the AAOI in Fig. 4 during SON. To help view the presence of outliers, areas within ± one standard deviation from the mean are shaded for both axes. The data from different decades are also plotted in different styles to help identify the changes by decade. The 1988 La Niña is clearly evident as an outlier (upper left hand corner in oval), showing a negative correlation unlike any other data point. The two boxed outliers in the lower left corner and one in the upper right corner all occurred during the 1990s, leading to the strong positive correlation during this decade. Thus, the 1988 La Niña event is further identified as an anomalous event when the SOI and the AAOI are out of phase. Clearly the coupling between the AAO and the Pacific SSTs is robust during SON in the 1990s, as indicated by the correlation between the SOI and the AAO and the regression plot in Fig. 3.

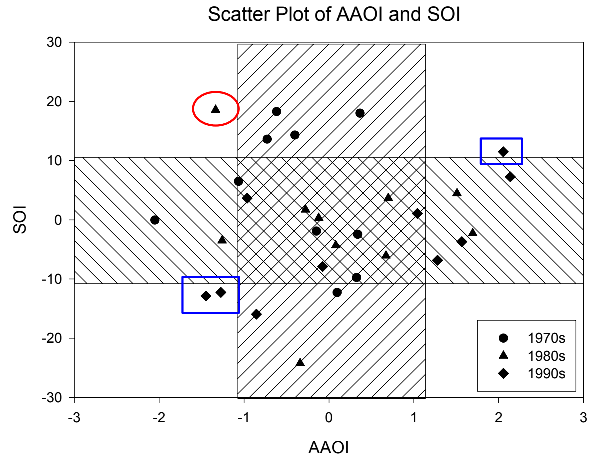

Figure 4. Scatter plot of the SON AAOI and SOI. Shaded regions indicate values within ±1 standard deviation. See text for detals.

5. Discussion

The increased coupling between the Southern Hemisphere circulation patterns captured by both the SOI and the AAOI in the 1990s is likely due to the increased frequency, duration, and magnitude of ENSO warm events observed within the last two decades. Earlier studies have demonstrated the significant impacts of the strong 1997-1998 El Niño followed directly by the moderate 1998-1999 La Niña on the Antarctic climate and the PSA wave train (Bromwich et al. 2004). Taken as a whole, the tropical Pacific SST variations have been stronger in recent times (1980-2000) compared to the last 50 years (i.e., Diaz et al. 2001, and references therein); not surprisingly, the teleconnection in the 1990s is the strongest of the last three decades.

Although the concept of the tropical SSTs forcing the AAO may be questioned in the SH, some connections have been established in the NH. Hoerling et al. (2001) using both observations and an atmospheric general circulation model (AGCM) show that the NAO, which is alternatively termed the Arctic Oscillation or Northern Annular Mode (e.g., Thompson and Wallace 2000), is related to the tropical SSTs in both the Pacific and Indian Oceans. Their study argues that the observed boreal winter trend in the NAO is intimately linked with the warming in the tropical SSTs, suggesting that the SSTs are forcing the NH extratropical climate. The analysis presented in this study is very similar to Hoerling et al. (2001), suggesting that this is also the case in the SH.

In the recent analysis by Chelliah and Bell (2004), connections are also made between the tropical circulation and the high latitude response in the Northern Hemisphere. They examine two PCs of the tropical circulation, the dominant one representing what they term the tropical multi-decadal mode (TMM), and the other representing the tropical inter-annual (ENSO) mode. Their study shows a linkage between the TMM and the NAO in DJF, in agreement with the findings of Hoerling et al. (2001). In DJF, they also find that the strongest ENSO teleconnections in subtropical regions of the Pacific and Africa occur when the TMM (related to the NAO) and ENSO are in phase, with stronger El Niño teleconnections existing from the 1980s to the 1990s. This finding is similar to the analysis presented here for the high latitudes of the Southern Hemisphere, as we find that the strongest ENSO teleconnections exist when the AAO and ENSO are in phase, which largely occurs during the 1990s.

It is not surprising to see the interaction between the AAOI and the SOI break down during the 1988 LN. A case study by Parish and Bromwich (1998) detailed decreases of surface pressure of up to 20 hPa across much of the Antarctic continent during late June and early July of 1988. These significant pressure decreases were associated with a breakdown of the meridional mass circulation over Antarctica that altered the meridional mass distribution as far north as the subtropical latitudes, thus impacting normal ENSO-induced circulations. By the austral spring, some of these large changes in the meridional mass distribution were still influencing the SH atmospheric circulation. It is likely that the anomalous Antarctic pressure decreases during the austral winter resulted in disruptions to the tropical teleconnection particularly during the austral spring, although detailed exploration of this conjecture warrants further study and is beyond the scope of this paper.

6. Summary

Decadal variability of the ENSO teleconnection in the South Pacific has been presented. This decadal variability is observed in many fields including MSLP (not shown) and geopotential height. Examining the decadal variability demonstrates that the strong teleconnection seen in the annual mean plots is dominated by the teleconnections during SON and DJF. The reduced teleconnection during the 1980s is readily explained by the lack of a response during SON in the 1980s; during DJF (not shown) the teleconnection remains strong for both the 1980s and the 1990s although its spatial representation is different.

Through Principal Components Analysis, the current study has shown that the high southern latitude ENSO teleconnection is manifested in the South Pacific during times when the AAOI is positively correlated to the SOI. The connections between ENSO and the Antarctic Oscillation appear only in the seasons when the ENSO forcing is particularly strong, namely austral spring and summer. Specifically, the 1988 SON LN event was associated with an anticorrelation between the AAOI and the SOI, which readily explains the overall decrease in the annual mean ENSO teleconnection during the 1980s.

The results presented here suggest that the tropical SSTs play an important role in the forcing of the high southern latitude tropospheric circulation, so that the two modes are closely linked in the most recent decade. It is unclear whether the coupling observed here between the high latitude SH circulation and ENSO is part of natural climate variability or climate change; the quality of the available reanalyses limit the study to the last 30 years or so. However, the associations depicted in the 1990s are the strongest observed in the last 30 years, in agreement with previous knowledge (e.g., Bromwich et al. 2004).

Acknowledgments. The authors would like to thank Zhichang Guo for the original design of the program used in calculating correlations with the SOI, Sheng-Hung Wang for PCA assistance, and Jorge Carrasco for supplying the 500 hPa zonal wind data for Punta Arenas. This research was funded in part by NSF grant OPP-0337948.

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