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Evidence for interannual and interdecadal climate variability in the South Atlantic

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Abstract. A singular value decomposition (SVD) analysis is used to determine the coupled modes of variability of monthly sea surface temperature (SST) and sea level pressure (SLP) data from the South Atlantic region, for the period 1953-1992. We find that the three leading SVD modes respectively account for 63%, 20% and 6% of the total square covariance. The first mode represents an approximately 15-year period oscillation in the strength of the subtropical anticyclone, accompanied by fluctuations of a north-south dipole structure in the SST. It appears to be linked to the global-scale interdecadal (15-year) joint mode in SST and SLP recently studied by Mann and Park. The second mode is characterized by east-west displacements of the anticyclone center, in association with strong 6 to 7-year period fluctuations of SST off the coast of Africa. The third mode is characterized by north-south displacements of the anticyclone and 4-year period fluctuations in the SST in a broad band across the central South Atlantic. This mode is strongly correlated with ENSO.

Introduction

In an attempt to better understand the nature and causes of natural climate variability on interannual and decade-to-century timescales, there have been many recent data and modeling studies of the large-scale linkages between the atmosphere and the ocean [e.g. see *Wallace et al.*, 1990; *Delworth et al.*, 1993; *Deser and Blackmon*, 1993; *Kushnir*, 1994; *Mann and Park*, 1996 and the references therein]. A detailed spatio-temporal knowledge of such climate variability is necessary in order to separate out possible anthropogenic climate change from these internal climate fluctuations. However, the focus of most of these studies has been on the climate variability of the northern hemisphere, whereas mankind-induced climate change is expected to have global impacts. Thus it is imperative that we gain an increased understanding of the space-time structure of natural climate variability in the vast southern hemisphere ocean-atmosphere climate system.

The main goal of this note is to present the highlights of an ongoing investigation of large-scale air-sea interactions on interannual and interdecadal timescales in one area of the southern hemisphere where the data coverage is reasonably good, namely, the South Atlantic. Monthly SST and SLP data from the post-war period 1953-1992 are analyzed jointly using the singular value decomposition analysis method [*Bretherton et al.*, 1992]. A secondary goal is to search for connections between the southern coupled modes of variability and familiar tropical and northern hemisphere climate fluctuations such as ENSO, the NAO and the PNA.

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Data and Methods

The data analyzed consist of South Atlantic sea surface temperature (SST) and sea level pressure (SLP) monthly means from the Comprehensive Ocean Atmosphere Data Set (COADS) [*Woodruff et al.*, 1987], for the 40-year period 1953 to 1992. The region south of 40°S and east of 40°W (see Figures 1-3) is not included in the study because of poor data coverage during this period. Monthly anomalies are computed from climatology and then smoothed in time by three-month running means. The spatial gaps in the data are next filled by using an inverse distance interpolation method. A singular value decomposition (SVD) is performed on the cross covariance matrix between the unnormalized SST and SLP anomalies to identify modes of behavior in which the variations of these quantities are strongly coupled [*Bretherton et al.*, 1992; *Wallace et al.*, 1992]. The spectral analysis performed on the SVD time series is based on the multi-taper method [*Thomson*, 1982], and their significance levels are computed relative to red noise [*Mann and Lees*, 1996]. The significance of each temporal correlation stated below is computed using the method described by *Sciremammano* [1979], which accounts for the month-to-month autocorrelation inherent in the time series. The 95% significance level is given in square brackets after each correlation coefficient.

SVD Analysis

The three leading SVD modes of the coupled SST and SLP fields account for 63%, 20% and 6% of the total square covariance, respectively. Figure 1, Figure 2 and Figure 3 show their associated spatial patterns, Sk(SST) and Sk(SLP), and time series of expansion coefficients, sk(SST) and sk(SLP), k=1,2,3. The "coupling" correlations between the SST and SLP time series of each mode are 0.46 [0.29], 0.30 [0.20] and 0.41 [0.21], respectively. These correlations indicate the strength of the coupling in each case. Thus, the atmosphere and ocean seem to be more strongly coupled in the first and third modes than in the second. Figure 4 shows the power spectra of the three time series sk(SLP). The spectra of sk(SST) exhibit similar structures and are not shown.

The robustness of the SVD results is assessed by testing the significance of the square covariance (SC) associated with each mode using a Monte Carlo approach.

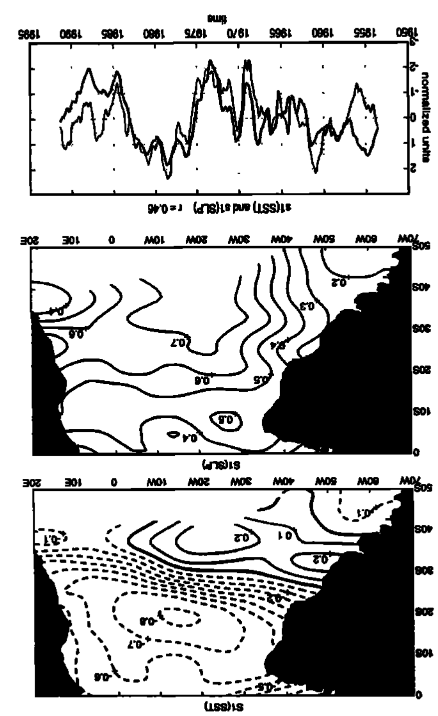

Figure 1. Spatial patterns (S1) and time series of expansion coefficients (s1) of the interdecadal SST and SLP coupled mode. Spatial patterns are presented as correlation maps between the time series s1(SST) and the grid point SST anomalies (top), and the time series s1(SLP) and the grid point SLP anomalies (middle). Negative contours are dashed. Zero line is thicker. Contour interval is 0.1. Time series (bottom) are smoothed by a 13-month running mean and amplitudes are normalized by the relevant standard deviation. Thick line is s1(SST), thin line is s1(SLP).

The SVD analysis is repeated 100 times linking the original SST data set with "scrambled" SLP data sets, so that the chronological order between SST and SLP is destroyed. However, only the years are scrambled; the seasonal structure inside each year is preserved, in order to maintain the month-to-month autocorrelation inherent in the time series and not to overestimate the significance of the modes. The SC values obtained from the random SVD do not exceed the original SC by more than 5 times, indicating that the obtained results are statistically significant at the 95% level.

Interdecadal Mode

The first coupled mode (Figure 1) can be described as an oscillation in the strength of the subtropical anticyclone, accompanied by fluctuations of a north-south dipole structure in the ocean temperature. A lagged correlation analysis between s1(SST) and s1(SLP) (not shown) indicates that the coupling is strongest when SLP leads SST by 1-2 months (correlation coefficient = 0.51 [0.29]). This suggests an atmosphere-to-ocean forcing, in which the ocean response to changes in the atmospheric circulation has an intraseasonal time lag.

An analysis of the wind anomalies associated with this mode (not shown) reveals that the observed wind-SST relationship is mainly local: stronger-than-normal winds coincide with cool ocean temperatures, while

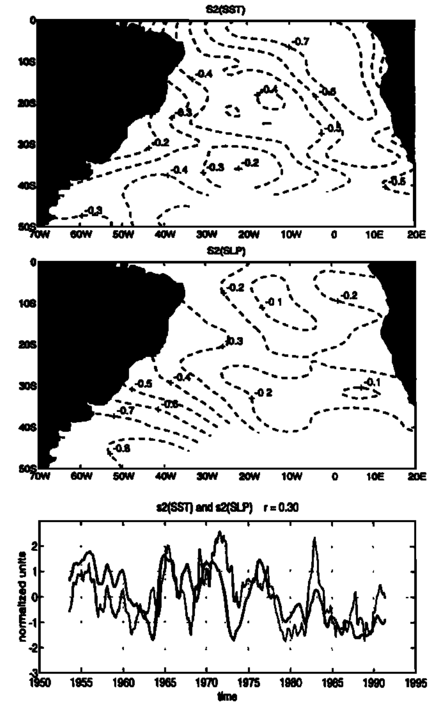

Figure 2. Spatial patterns (S2) and time series of expansion coefficients (s2) of the low frequency interannual SST and SLP coupled mode. Conventions as in Figure 1.

weaker-than-normal winds coincide with warm ocean temperatures. Also, southerly (northerly) winds are associated with negative (positive) SST anomalies. This indicates that local wind-induced mechanisms (such as changes in the air-sea heat fluxes and entrainment)

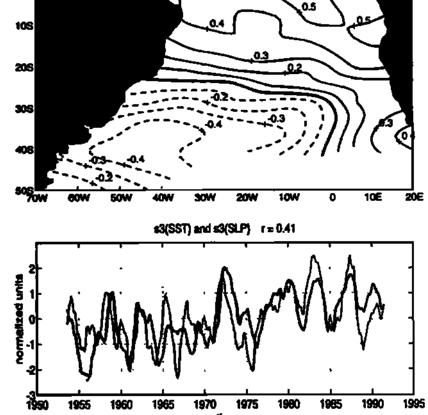

Figure 3. Spatial patterns (S3) and time series of expansion coefficients (s3) of the high frequency interannual SST and SLP coupled mode. Conventions as in Figure 1.

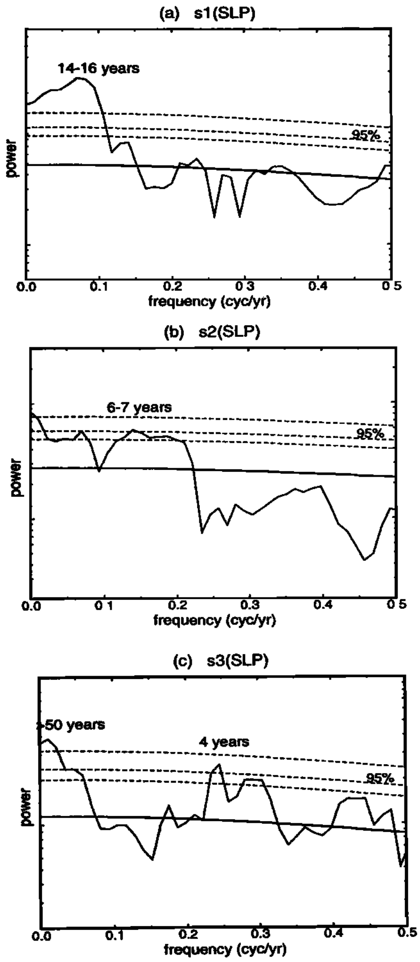

Figure 4. Power spectra of the time series: (a) s1(SLP), (b) s2(SLP) and (c) s3(SLP) shown in Figures 1-3. The spectra of the associated s1(SST), s2(SST) and s3(SST) are similar. Dashed lines are 90%, 95% and 99% significance levels.

may contribute to the generation of the SST anomalies [*Deser and Blackmon*, 1993; *Kushnir*, 1994].

The spectra of both s1(SST) and s1(SLP) (Figure 4a) exhibit highly significant peaks at low frequencies (period of ~ 14-16 years), indicating that such fluctuations in the strength of the anticyclone are dominated by interdecadal timescales. Oscillations with similar timescales (~ 15-year period) have also been identified in global air and sea surface temperature (using frequency-domain analyses) by *Folland et al.* [1984], *Ghil and Vautard* [1991], and *Mann and Park* [1994].

The fluctuations of this South Atlantic interdecadal mode of variability are significantly correlated with those of the interdecadal joint mode of northern hemisphere surface temperature and SLP found by *Mann and Park* [1996]. The South Atlantic signal leads their reference signal (projected onto North Pacific SLP) by 4-5 years (correlation coefficient = 0.89 [0.80] using a 5-yr running mean to smooth the noise in the monthly data). It is worth noting that the co-spectrum between the two series shows a significant peak at a period of 17.5 years (M. E. Mann, personal communication), which indicates that both signals fluctuate at this preferred timescale. Furthermore, Mann and Park's analysis indicates that the northern hemisphere anomalies associated with the interdecadal signal are most pronounced during the northern winter. This is simultaneous with the South Atlantic signal, which is strongest during the southern summer, as revealed by a SVD analysis of seasonal data. We suggest that the northern and southern hemisphere signals may be parts of a larger, inter-hemispheric mode of interdecadal variability.

Low Frequency Interannual Mode

The second coupled mode of variability (Figure 2) is characterized by east-west displacements of the subtropical anticyclone, accompanied by strong SST fluctuations over a wide region off the coast of Africa. A pressure trough appears off the Argentine coast and the circulation becomes more meridional when the anticyclone is at its easternmost position. This situation is associated with a negative SST anomaly near the coast of Africa.

Lagged correlations between s2(SST) and s2(SLP) (not shown) indicate that the two fields are best correlated at zero lag (correlation coefficient = 0.30 [0.20]). Even though the coupling correlation is relatively weak, the zero-lag correlation is suggestive of an ocean-to-atmosphere forcing, in which the atmospheric response to changes in the ocean appears with a time lag of less than a month. This is supported by the lack of evidence for wind driving the SST anomalies. For example, the wind pattern associated with this mode (not shown) does not appear to be consistent with local wind-induced processes driving the SST anomalies. Additionally, a lagged correlation between SST and wind indices for a 4°-box centered at 0°,10°S (the center of action of S2(SST)) shows no significant correlation for wind leading SST up to 10 months.

The spectra of both s2(SST) and s2(SLP) (Figure 4b) exhibit a significant peak at ~ 6-7 years, indicating that this mode is dominated by relatively low frequency interannual variations. A similar period of oscillation has been found by *Ghil and Vautard* [1991] in a frequency analysis of global temperature data.

A co-spectrum between s2(SLP) and the North Atlantic Oscillation (NAO) index shows a significant peak at a period of ~ 5 years, indicating that both the North and South Atlantic oscillations fluctuate with similar frequencies. A co-spectrum between s2(SLP) and the SOI shows a significant peak at 6 years, which suggests that this mode may also be associated with the lower-frequency variability of ENSO. *Rogers* [1984], on the other hand, observed a link between NAO and SOI at a period of 5.7 years. Taken together, these results indicate that all three signals (NAO, SOI and this South Atlantic mode) may be related at a low frequency interannual timescale.

High Frequency Interannual Mode

The third coupled mode (Figure 3) is characterized by north-south displacements of the subtropical anticyclone, accompanied by SST fluctuations over a latitudinal band centered around 25-30°S and extending across the South Atlantic. A northward shift in the location of the subtropical anticyclone is associated with warming of the ocean temperature in the central South Atlantic. The time series s3(SST) and s3(SLP) are best correlated when SLP leads SST by 1-2 months (correlation coefficient = 0.42 [0.21]), suggesting again an atmosphere-to-ocean driving. The wind pattern associated with this mode (not shown) reveals a weakening of the climatological easterly winds around 25°S due to a westerly wind anomaly associated with the strong north-south SLP gradient in Figure 3 (middle). The weaker-than-normal easterlies in this band result in smaller-than-normal heat losses from the ocean to the atmosphere. This produces a zonally oriented positive SST anomaly (see Figure 3, top). Further support for atmosphere-to-ocean forcing comes from a lagged correlation analysis between zonal wind and SST indices for a box centered at 25°W-25°S (the center of action of S3(SST)), which shows a significant correlation for the wind leading the SST by 2 months (correlation coefficient = 0.15 [0.11]).

A connection between this mode of variability and El Niño-Southern Oscillation (ENSO) is revealed by a significant correlation of both s3 time series with the Southern Oscillation Index (SOI) lagged at 1-2 months, indicating that a warming in the central South Atlantic leads a warming in the equatorial Pacific (correlation coefficient = 0.37, [0.20]). The spatial patterns in Figure 3 are in good agreement with the ENSO-related patterns of the same variables found by others over the same region [*Enfield and Mayer*, 1995; *Peixoto and Oort*, 1992].

The power spectra of s3(SST) and s3(SLP) (Figure 4c) exhibit significant peaks at a period of $\sim$ 4 years, comparable to typical ENSO timescales. Thus, it is not surprising that the co-spectra between the two s3 time series and the SOI show significant peaks at 4-5 years. A co-spectrum between s3(SLP) and the Pacific/North American (PNA) index, on the other hand, has a broad significant peak at quasibiennial timescales (2.3 to 2.7-year periods). Lagged correlations of the PNA index with s3(SLP) and s3(SST) indicate that the positive phase of the PNA reaches its maximum $\sim$ 6-7 months after the northward shift of the South Atlantic subtropical anticyclone and the warming in the central South Atlantic.

A positive trend is also detectable in both s3(SST) and s3(SLP) (Figure 3, bottom). This trend is in good agreement with the century-scale (90-100 year period) oscillation in global surface temperature found by *Mann and Park* [1994], which from $\sim$ 1940 to the present shows a strong cooling in the northern North Atlantic occurring simultaneously with a warming in the South Atlantic.

Conclusions

The analysis of the coupled variations of the SST and SLP fields in the South Atlantic since 1953 indicates the presence of both interannual and interdecadal timescales. In order of importance, these variations are characterized by periods of $\sim$ 15 years, $\sim$ 6-7 years and $\sim$ 4 years. These (or very similar) periods of oscillation appear to be the common timescales for interannual and interdecadal climate variability, which have frequently been observed in the fluctuations of oceanic and atmospheric variables by other investigators [*Folland et al.*, 1984; *Ghil and Vautard*, 1991; *Mann and Park*, 1996; *Latif and Barnett*, 1994].

The interdecadal mode accounts for most of the variance in the two fields and can be described as a "strong-weak" subtropical anticyclone oscillation which forces (with a lag of 1-2 months) a dipole structure in the ocean temperature. The low frequency interannual mode is characterized by east-west displacements of the subtropical anticyclone which occur simultaneously with large SST fluctuations off the coast of Africa. The high frequency interannual mode is characterized by north-south displacements of the subtropical anticyclone followed (with a lag of 1-2 months) by SST fluctuations over a latitudinal band in the central South Atlantic ocean. This mode is strongly related to ENSO.

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