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Negative ocean-atmosphere feedback in the South Atlantic Convergence Zone

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[1] The temporal evolution of the coupled variability between the South Atlantic Convergence Zone (SACZ) and the underlying sea surface temperature (SST) during austral summer is investigated using monthly data from the NCEP/NCAR reanalysis. A maximum covariance analysis shows that the SACZ is intensified [weakened] by warm [cold] SST anomalies in the beginning of summer, drifting northward. This migration is accompanied by the cooling [warming] of the original oceanic anomalies. The results confirm earlier analyses using numerical models that suggest the existence of a negative feedback between the SACZ and the underlying South Atlantic SST field. A linear regression of daily anomalies of SST and omega at 500 hPa to the equations of a stochastic oscillator reveals a negative ocean–atmosphere feedback in the western South Atlantic, stronger during January and February directly underneath the oceanic band of the SACZ. **Citation:** De Almeida, R. A. F., P. Nobre, R. J. Haarsma, and E. J. D. Campos (2007), Negative ocean-atmosphere feedback in the South Atlantic Convergence Zone, *Geophys. Res. Lett.*, *34*, L18809, doi:10.1029/2007GL030401.

1. Introduction

[2] The South Atlantic Convergence Zone (SACZ) is a band of convective activity extending from the Amazon forest to the southwestern South Atlantic ocean [*Kodama*, 1992], predominant during the austral summer (January–February–March, JFM) and exhibiting temporal variability on a broad range of scales. Interannual variability of JFM precipitation associated with the system has a magnitude of 10 mm day^{-1} over the continent, comparable to the climatological mean [*Barreiro et al.*, 2005]. There is also considerable variability both in submonthly [*Liebmann et al.*, 1999] and intraseasonal [*Nogués-Paegle and Mo*, 1997] timescales.

[3] The relationship between the intensity and position of the SACZ together with the underlying Sea Surface Temperature (SST) anomalies is still not fully understood. *Figueroa et al.* [1995] suggested that the SST field is not important for the SACZ formation, since the position of the band of maximum convection does not coincide with climatological warm SST on the South Atlantic. *Barreiro et al.* [2002] estimated through numerical modeling that approximately 60% of the total precipitation variance in the SACZ region is explained by the internal variability of the atmosphere. Nevertheless, their work suggests that a considerable fraction of the remaining variability can be explained as a response to the oceanic forcing, representing an atmospheric adjustment to SST anomalies in the southwestern part of the South Atlantic basin. This adjustment, however, appears in the observations with a paradoxical nature: the analyses done by *Robertson and Mechoso* [2000] show that an intensification of the convective activity in the SACZ is accompanied by negative (cold) basin-wide SST anomalies.

[4] *Chaves and Nobre* [2004] showed that warm [cold] SST anomalies are able to intensify [weaken] the SACZ in an atmospheric general circulation model (AGCM) through the low-level convergence of moisture, shifting it northward. The associated increase in cloudiness, in turn, causes the appearance of cold SST anomalies or the weakening of pre-existing warm SST anomalies in a ocean general circulation model (OGCM) through the reduction of the incident shortwave solar radiation. This negative feedback mechanism suggests that the observed cold SST anomalies that usually appear together with the intensified SACZ are generated after an initial atmospheric response to warm anomalies (i. e., SST+ ⇒ SACZ+ ⇒ SST−).

[5] In this letter we analyze the covariance of oceanic and atmospheric fields from the NCEP/NCAR reanalysis during the austral summer to investigate the existence of a negative feedback between South Atlantic SST anomalies and the convective activity associated with the SACZ. A simple model of the stochastic oscillator is then used to characterize the intensity and the spatial configuration of the observed feedback in the South Atlantic basin. The structure of this letter is as follows: in section 2 we briefly describe the data used. The pattern describing the temporal evolution of the SACZ–SST interaction is investigated in section 3, followed by an application of the stochastic oscillator in section 4. A short discussion and a summary are finally presented in section 5.

2. Data

[6] The data used for this study were obtained from the NCEP/NCAR reanalysis [*Kistler et al.*, 2001], shown to be adequate in several studies of tropical and subtropical variability on intraseasonal [e.g., *Kiladis and Weickmann*, 1997; *Liebmann et al.*, 1999] and decadal [e.g., *Sterl*, 2001a, 2001b] timescales. We used omega at 500 hPa (W500) as a proxy for the SACZ, since the intensity of the SACZ is intrinsically related to vertical air displacement associated with low-level convergence [*Robertson and Mechoso*, 2000]. Daily and monthly mean anomalies from

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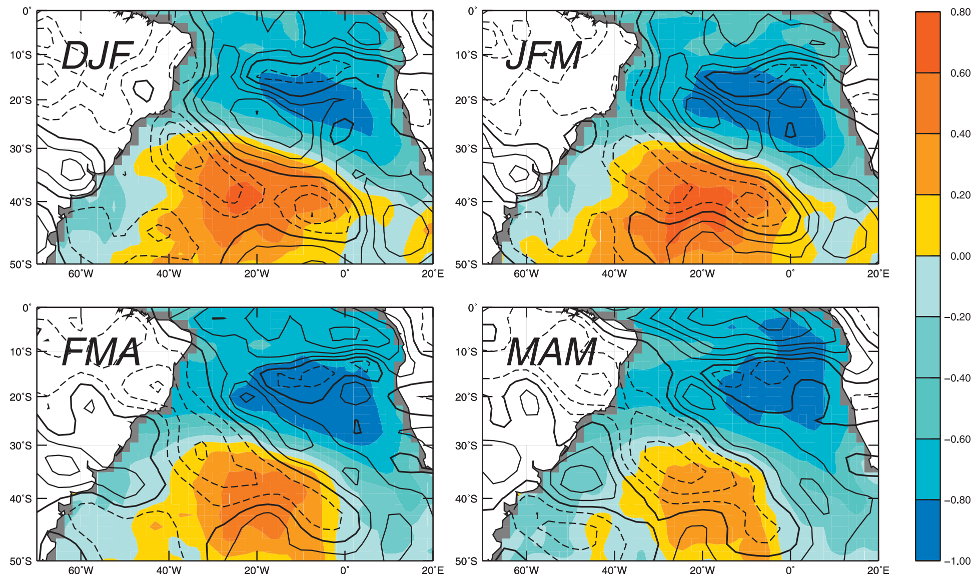

Figure 1. First heterogeneous W500 (Contour Interval = 0.1 Pa s^{-1}, negative values dashed) and homogeneous SST (colors, interval = 0.2 K) covariance maps for the monthly triplets of December–January–February (DJF), January–February–March (JFM), February–March–April (FMA) and March–April–May (MAM).

the mean seasonal cycle for the period between 1980-01-01 and 2005-12-31 were calculated using a linear adjustment of annual and semi-annual frequencies [*Podestá et al.*, 1991], and linearly detrended using a first order polynomial adjustment. The anomalies were also normalized by a domain averaged seasonal cycle of one standard deviation to give similar weight to each month. We restricted our analyses to the period from 1980 to present due to the inhomogeneity of the data when compared to the ECMWF ERA-40 [*Sterl*, 2004] being particularly strong in the South Atlantic ocean.

3. SACZ–SST Interaction

[7] We investigated the large-scale patterns of covariability between the ocean and the atmosphere conducting a maximum covariance analysis (MCA) based on a singular value decomposition of the covariance matrix between SST and W500 anomalies [*Czaja and Frankignoul*, 2002] considering the South Atlantic basin (70°W to 20°E, 50°S to Equator). As we wanted to characterize the seasonal evolution of the covariance between SST and W500, we conducted the MCA four different times using monthly triplets [e.g., a field composed of monthly mean anomalies from December–January–February (DJF)] starting at the beginning of the austral summer until May and considering only the first pattern (“SVD”) from each analysis.

[8] Figure 1 shows the results from the analyses, depicting the temporal evolution of the coupled pattern of SST–W500 interaction during DJF, January–February–March (JFM), February–March–April (FMA) and March–April–May (MAM). We present the results as homogeneous maps for the ocean and heterogeneous maps for the atmosphere, since they preserve linear relations between the variables [*Czaja and Frankignoul*, 2002], and the correlation maps are scaled to represent the amplitudes of the anomalies associated with one standard deviation of the SST time series. A Monte Carlo test was used to assess the robustness of the maps at the 95% significance level. Each MCA was repeated 100 times, scrambling the months in the SST series to remove any chronological order between oceanic and atmospheric variables. Significance was then indicated by the number of realizations with higher squared covariance in comparison with each MCA.

[9] The first MCA for DJF, on the top-left panel, shows a band of negative W500 (dashed) extending from the NE of Brazil onto the southern region of the South Atlantic, corresponding to an event where the SACZ is intensified [weakened, depending on the sign of the time series associated with the map]. This atmospheric pattern is accompanied by underlying warm [cold] SST anomalies on the southwestern part of the basin of up to 0.8 K. This pattern represents 38% of the coupled SST–W500 variability, and the time series associated with the oceanic and atmospheric maps have a correlation coefficient of 0.67.

[10] During JFM (top-right panel) the maps are mostly unchanged, and although the variance explained by the pattern is greatly reduced to 11%, the mode is still strongly coupled ($r = 0.67$). Afterwards, the results from FMA (41%, $r = 0.60$) and MAM (16%, $r = 0.66$) reveal that during this period the SACZ is shifted towards north during the evolution of the coupled mode while maintaining its intensity; the initial SST anomaly, on the other hand, has its amplitude reduced to a maximum of 0.2 K and is greatly diminished in area. At the end of the period the South Atlantic is largely dominated by cold [warm] basin-wide SST anomalies, together with a strengthened [weakened] SACZ over the NE of Brazil.

[11] The dominant modes of coupled variability displayed by the SST and W500 anomalies in the NCEP/NCAR reanalysis during the austral summer are consistent with the results found by *Chaves and Nobre* [2004] in numerical models, corroborating the theory of a negative thermodynamic feedback between cloud/shortwave radiation and SST involving the SACZ and the South Atlantic. This negative feedback is apparently triggered by a basin-wide dipolar pattern of SST that is able to affect the SACZ

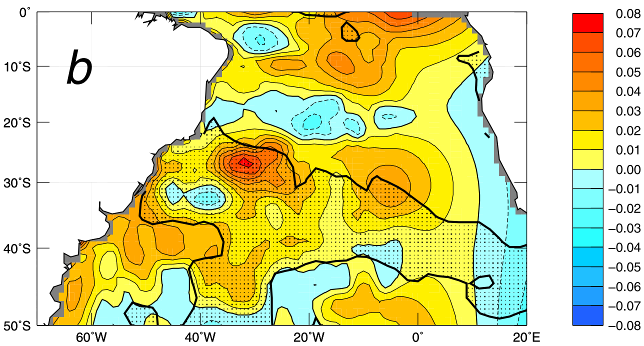

Figure 2. Spatial map of the coupling parameter b (adimensional, CI = 0.01, negative values dashed) from equation (3) for daily SST and W500 anomalies during the months of January and February. The hachure with a thick border indicates regions where the SST cooling between DJF and MAM from the MCA is larger than 0.2 K.

over the southwestern South Atlantic, being in turn damped by the forced SACZ at the end of the austral summer. In order to characterize this feedback quantitatively, we used a simple parametric model of the stochastic oscillator to represent the ocean–atmosphere interaction in the region, as described on the next section.

4. Stochastic Oscillator

[12] The stochastic oscillator is a simple parametric model of two variables in which noise is responsible for maintaining an irregular cycle [*Burgers*, 1999]. The concept of the stochastic oscillator has been applied to the solution of a broad range of problems, from climate variability in the Tropical Atlantic [*Chang et al.*, 1997] to interdecadal variations of the thermocline [*Rivin and Tziperman*, 1997]. The discrete parametric form of the stochastic oscillator is given by the two equations

$$x_{i+1} = a_1 x_i - b y_i + \xi_i \quad (1)$$

$$y_{i+1} = b x_i + a_2 y_i + \eta_i, \quad (2)$$

where x and y are adimensional variables giving the two degrees of freedom of the system and a_1, a_2 and b are adimensional constants. The terms ξ and η correspond to the stochastic noise, and may be correlated. The index i represents the discrete time step.

[13] These two simple equations capture the essence of the negative feedback between W500 and SST anomalies: associating the variable x to W500 and relating y to SST, equation (1) predicts that future values of W500 depend on a "memory" a_1 and on a coupling parameter b negatively related to the SST; the result is that warm (positive) SST anomalies tend to reduce W500 and, consequently, strengthen the SACZ. Equation (2), on the other hand, describe SST anomalies as determined by the memory a_2 and a *positive* coupling with the term b; negative anomalies of W500, corresponding to an intensified SACZ, tend to cool SST anomalies, reproducing the negative feedback proposed by *Chaves and Nobre* [2004].

[14] Combining equations (1) and (2) we arrive on a single equation that can be used to quantify the negative feedback, measured by the parameter b, of the SACZ–SST system in the South Atlantic:

$$y_{i+1} = a_2 y_i + a_1 b x_{i-1} - b^2 y_{i-1} + \epsilon_i \quad (3)$$

[15] We conducted a linear regression of equation (3) to daily SST and W500 anomalies from the NCEP/NCAR reanalysis normalized by the local standard deviation, minimizing the total noise ϵ_i to estimate the parameter b on each grid point of the basin. For this, the W500 data was regridded to match the finer SST grid, and a 25-day Hann window was applied to both datasets to remove high frequency variability from the fields and maximize the coupling between oceanic and atmospheric variables. Parameters a_1 and a_2 were estimated from the local auto-correlation of each variable. The linear regression was initially performed using daily W500 and SST anomalies from January to December, resulting in negligible values for the coupling parameter b for all the South Atlantic (not shown). We repeated the analysis using only data for the months of January and February, when the SACZ is more intense; the result is shown in Figure 2.

[16] The picture illustrates the spatial distribution of the parameter b over the South Atlantic ocean, together with regions where the SST cooling from DJF to MAM is larger than 0.2 K. A Markov Chain Monte Carlo simulation [*Berg*, 2005] shows that on the SACZ region the significance threshold for b varies between 0.025 and 0.04. It is clear from the picture that the feedback between W500 and SST predominates underneath the SACZ band, extending from approximately 25°S, 45°W to 40°S, 10°W and following the overall pattern of surface cooling with a slight northward shift. In this region, the adimensional parameter reaches values of up to 0.08, indicating that a small part of the SST–W500 variability in that region during the austral summer is determined by the local negative feedback. Outside the SACZ band, b assumes smaller values of up to 0.03, increasing lightly towards the eastern Tropical Atlantic. The map also displays negative values of the parameter b, indicating regions at the border of the SACZ band where the negative feedback is inverted (i. e., SST+ $\Rightarrow$ SACZ− $\Rightarrow$ SST−).

[17] The unnormalized (dimensional) parameter b on the maximum feedback region has a magnitude of 0.4 K Pa^{-1} s, for a coupling timescale of approximately 25 days. This corresponds to a cooling of order 0.15 K per month with the SACZ intensified by an anomaly of 0.3 Pa s^{-1} such as depicted on the MCA in Figure 1. This cooling is consistent with the damping of SST anomalies observed in the MCA analyses, slightly overestimating the observed reduction from 0.8 K to 0.4 K during a period of 4 months (DJF to MAM).

5. Discussion

[18] In this study we investigated the negative feedback between the SACZ and the South Atlantic SST anomalies during the austral summer. The main motivation of this study was to confirm the existence of a negative thermodynamic feedback involving the SACZ and the underlying

SST field, first described in uncoupled numerical experiments [*Chaves and Nobre*, 2004]. This feedback consists of an initial atmospheric response to the local SST. In the case of warm SST anomalies the response consists of the intensification and northward migration of the SACZ, followed by the damping of the oceanic anomalies due to the blocking of incoming solar radiation by the increase in cloudiness.

[19] Our results demonstrate that this pattern appears as a dominant mode of variability in anomalous fields of SST and W500 from the NCEP/NCAR reanalysis, as shown from the correlation maps from the MCA. The existence of the negative ocean–atmosphere feedback in the data is demonstrated using the equations from the stochastic oscillator, and quantified from the coupling parameter b. Fitting the model to the data shows that the feedback is strongest in the South Atlantic beneath the SACZ band during austral summer, as expected. The small magnitude of the coupling shows that the signal-to-noise ratio is low, with the oceanic and atmospheric processes being dominated by non-local forcing.

[20] The spatial pattern of negative feedback is stronger on the northward part of the SACZ band, shifted in regard to the cooling observed between the covariance modes of DJF and MAM. This shift can be explained by the migration of the SACZ in the same direction during that period: the northern border of the SACZ initially contains SST and W500 anomalies with small amplitudes (Figure 1), but as the SACZ intensifies and migrates northward this region is subject to strong anomalies of W500 generated southward, where the SST anomalies have large amplitudes. The result is a strong damping of the SST anomalies and the overestimation of the local negative feedback in regions north of where the SACZ is initially formed.

[21] The same mechanism explains the ocurrence of regions in Figure 2 where the b parameter is negative, close to the borders of the SACZ band. While the region at 30°S, 40°W initially displays positive SST anomalies during DJF (Figure 1), after the migration of the SACZ in MAM it is affected by positive W500 anomalies generated by subsiding air due to mass conservation, resulting in a weak negative feedback with an inverted coupling (SST+ $\Rightarrow$ SACZ− $\Rightarrow$ SST−). A similar effect occurs on the 20°S latitude, where negative SST anomalies are affected by the SACZ migrating from the south. Negative values of b appear here when the original cold SST has its amplitude damped by non-local processes, suggesting a negative feedback where negative SST anomalies are warmed by an intensified SACZ (SST− $\Rightarrow$ SACZ+ $\Rightarrow$ SST+).

[22] In spite of the small values of b, these results have positive implications for the predictability of the SACZ in South America. The stochastic model predicts intraseasonal variations of the SACZ and the SST, and is possibly linked with large-scale climate dynamics. The dipolar pattern of SST that triggers the feedback (see DJF map from Figure 1) is correlated in time (r = 0.98) and space (r = 0.85) with the dominant mode of coupled mean sea level pressure (MSLP)/SST decadal variability for the South Atlantic [*Venegas et al.*, 1997; *Sterl and Hazeleger*, 2003; *Haarsma et al.*, 2005], revealing that the feedback pattern varies on timescales longer than intraseasonal and may be linked to large-scale modulations of the Southern Hemisphere mid-latitude atmospheric circulation [*Hermes and Reason*, 2005].

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