Local and remote sources of tropical atlantic variability as inferred from the results of a hybrid ocean-atmosphere coupled model

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[1] A hybrid ocean-atmosphere coupled model is used to study the interannual variability of sea surface temperature and wind stress over the tropical Atlantic. The coupled model is composed of a statistical atmospheric component model that uses sea surface temperature anomalies (SSTA) over the tropical oceans to forecast wind stress anomalies over the tropical Atlantic, coupled to a general circulation model of the ocean configured over the Atlantic. It is shown that, while the Atlantic-only hybrid coupled model has damped oscillations of SSTA and wind stress, the inclusion of Pacific SSTA variability in the coupled model resulted in sustained oscillations of wind stress and SSTA over the equatorial Atlantic. *INDEX TERMS:* 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4215 Oceanography: General: Climate and interannual variability (3309); 4251 Oceanography: General: Marine pollution; 4504 Oceanography: Physical: Air/sea interactions (0312); 4263 Oceanography: General: Ocean prediction. **Citation:** Nobre, P., S. E. Zebiak, and B. P. Kirtman, Local and remote sources of tropical atlantic variability as inferred from the results of a hybrid ocean-atmosphere coupled model, *Geophys. Res. Lett.*, *30*(5), 8008, doi:10.1029/2002GL015785, 2003.

1. Introduction

[2] There is modeling evidence suggesting that equatorial Atlantic sea surface temperature (SST) interannual variability is locally damped. *Zebiak* [1993] and *Chang et al.* [2001] suggested that local air-sea coupling in the tropical Atlantic is probably not strong enough to maintain a self-sustained oscillation of the coupled system. *Zebiak* [1993] suggested that perturbations propagating from outside of the equatorial Atlantic region are necessary to explain the observed SSTA oscillations. *Chang et al.* [2001] used stochastic forcing to generate sustained variability over the deep tropics in a hybrid coupled model of the northern tropical Atlantic sector. Other studies [*Hameed et al.*, 1993; *Bengtsson et al.*, 1994; *Enfield and Mayer*, 1997; *Nicholson*, 1997; *Reason et al.*, 2000; *Saravanan and Chang*, 2000] also suggested the existence of teleconnections from the Pacific ENSO, influencing SST variability over the tropical Atlantic. Recently, *Huang et al.* [2002] used a regionally coupled CGCM over the tropical Atlantic Ocean but with prescribed SST over the global oceans to examine the remote influence of ENSO on tropical Atlantic air-sea interactions. They suggest that the northern tropical Atlantic SSTA is modulated by ENSO, but that the southern tropical Atlantic variability is determined essentially by local processes.

[3] This study focuses on possible remote sources of variability of the equatorial Atlantic SSTA, using a hybrid ocean-atmosphere coupled model of the tropical Atlantic Ocean. The structure of this paper is as follows: The following section describes the component models and data used for the study. In the next section the results of the several forced and coupled experiments are described. The final section presents our conclusions.

2. Methodology and Data

[4] The hybrid model used in this work consists of a canonical correlation analysis (CCA) based predictive model of surface wind stress coupled to GFDL's MOM2 ocean general circulation model configured over the tropical Atlantic basin. The CCA algorithm [*Bretherton et al.*, 1992] uses SSTA over the tropical Pacific and Atlantic (30°S–30°N; 180°W–20°E) as the predictor variable, to compute the surface wind stress over the tropical Atlantic between 30°S and 30°N. The data sets used are COADS SST and surface wind stress for the period January 1950 to December 1993 [*Da Silva et al.*, 1994] and NCEP's OI SST for the period 1981–1995. Surface wind stress for the period January 1960 to December 1995 are from NCEP reanalyzes. Long-term trends were removed from COADS wind stress and SST data sets (to assure that the long-term means are stationary). No long-term trends were detected in sea level pressure (SLP) or in its meridional derivative (following geostrophic arguments), suggesting that the removed trends from the surface wind stress are spurious. COADS data was used to train the CCA model, while OI SST and NCEP reanalyzes data were used in the numerical simulations. COADS/OISST and NCEP products were used in order to cover the whole period of study, from Jan/1950 to Dec/1995.

[5] The ocean model is version 2 the GFDL MOM configured with 20 levels in the vertical over the area 60°S–60°N over the Atlantic Ocean. Horizontal resolution is 1° zonal, 2° meridional, with enhanced resolution of 0.5° in the equatorial region. The vertical mixing scheme of heat,

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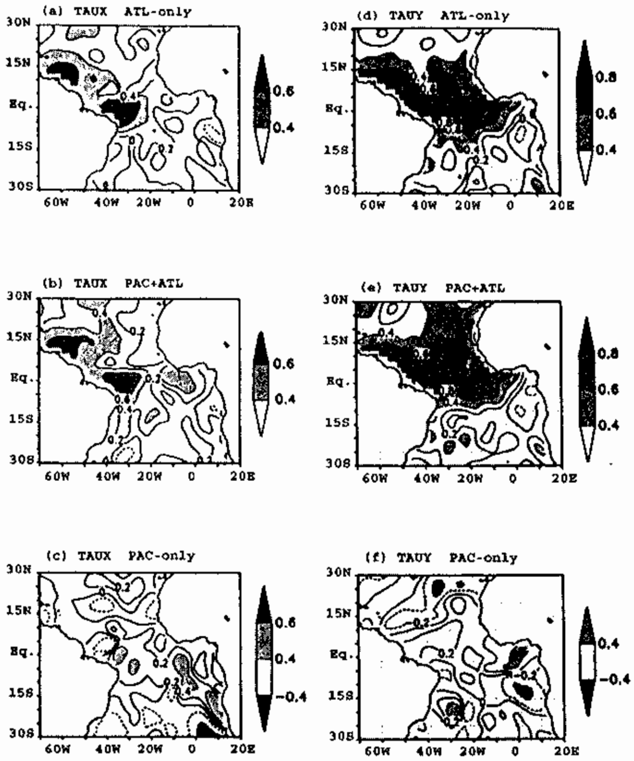

Figure 1. Anomaly correlation maps between CCA simulated Taux (left column), Tauy (right column), and COADS observations for (a, d) Atlantic-only; (b, e) Pacific + Atlantic; and (c, f) Pacific-only CCA models for the period January 1980 to December 1993. Shaded areas are statistically significant correlation.

momentum and salinity is Richardson number dependent [*Pacanowski and Philander*, 1981] and constant horizontal mixing of momentum (a detailed description of the model can be found in *Carton et al.* [2000]). Surface heat fluxes into the OGCM are parameterized according to *Seager et al.* [1995] atmospheric mixed layer (AML) model, and is composed of radiative, sensible, and evaporative components. Air humidity and surface air temperature used for the computation of surface heat fluxes are computed by the AML model, based on simulated SST. Partial cloud cover data used for the AML model are climatological.

[6] The computation of predicted surface wind stress is done as follows: SST anomalies from observations and or OGCM simulation are projected on SSTA EOFs. The projection coefficients obtained are then used with eight canonical modes and wind stress EOFs to compute the zonal and meridional components of surface wind stress anomalies, which are then inflated by local wind stress standard deviations and added to observed wind stress climatology. The wind stress field thus obtained is used to force the OGCM, which will generated a new SST field. The coupling frequency is daily. The training period used to derive the cannonical modes is January 1950 to December 1979.

3. Results

[7] Three CCA models were built, based on the predictor SSTA domains: 1) Atlantic-only, 2) Pacific + Atlantic, and 3) Pacific-only areas. Figure 1 shows the anomaly correlation coefficients between observed and CCA-computed wind stresses monthly time series for the period January 1980 to December 1993 (the validation period) for each CCA model. Anomaly correlation values higher than 0.4 in Figure 1 are 99% significant. Inspection of Figure 1 shows that the anomaly correlation values are statistically significant over the entire equatorial and part of the northern tropical Atlantic for the Atlantic-only (Figures 1a, 1d) and the Pacific-Atlantic (Figures 1b, 1e) CCA models. The area covered by statistically significant correlation for the Pacific-only CCA model results (Figures 1c, 1f) are considerably smaller than the other two CCA models. This result, alone, indicates that in linear terms, Pacific SSTA induced wind stress variability over the tropical Atlantic is less pronounced than the local SSTA effect.

4. Coupled Experiments

[8] A 60 year spin up integration of the OGCM is done to initialize the ocean in the coupled experiments. A total of six experiments are done with different wind stress products, as depicted in Table 1. Experiment 1 uses observed wind stress, while experiments 2–6 use the CCA models' wind stress. Experiment 2 is partially coupled, since the CCA model uses observed SSTA over the Pacific and simulated SSTA over the Atlantic to computed the surface wind stress anomalies over the tropical Atlantic. Experiment 3 is fully coupled, as it uses Atlantic-only simulated SSTA to compute the stress anomaly fields with the Atlantic CCA model. Experiments 4–6 are uncoupled and use observed SSTA everywhere to compute the CCA stresses.

[9] Figure 2 shows the area averaged SSTA time series over the equatorial Atlantic for all the experiments and for observations. The anomaly correlation coefficients (AC) and root mean squared (RMS) differences between the pair of curves in each panel in Figure 2 are shown on top of each panel. The equatorial Atlantic is chosen for the SSTA time series analysis, since the CCA derived winds (and thus forcing for the ocean) are best near the equator (see Figure 1).

[10] Forced experiment 1 (Figure 2a) and uncoupled experiments 4 (Figure 2d) and 5 (Figure 2e) have equatorial Atlantic SSTA variability that closely resemble observations. For the case of the partially coupled Pacific + Atlantic experiment 2 (Figure 2b), the equatorial Atlantic SSTA variability has magnitudes that are comparable to observations, though with less coherent phase agreement with the observed SSTA. Yet, coupled experiment 2 generates sustained oscillations, sharply contrasting with

Table 1. Summary of the Numerical Experiments Done

Experiment	OGCM	Wind Stress	Area of SSTA predictor
1	Forced	Observed	N/A
2	Partially Coupled	CCA simulated	Observed PAC + Simulated ATL
3	Coupled	CCA simulated	Simulated ATL-only
4	Uncoupled	CCA simulated	Observed PAC + ATL
5	Uncoupled	CCA simulated	Observed ATL-only
6	Uncoupled	CCA simulated	Observed PAC-only

Column 1: experiment No.; Column 2: type of model (forced/coupled/uncoupled); column 3: type of wind stress product; column 4: area of the predictor SSTA field for the CCA model.

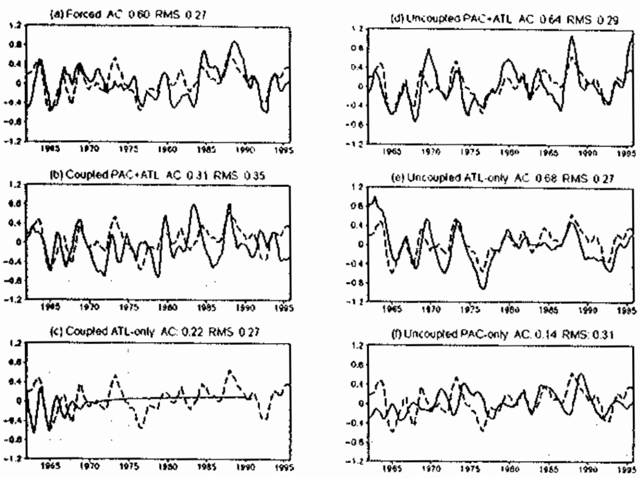

Figure 2. Time series of area averaged-12 months running means of simulated SSTA over the equatorial Atlantic (5°S–5°N) for experiments: (a) 1 (forced OGCM); coupled (b) 2 (Pacific + Atlantic); and (c) 3 (Atlantic-only); and uncoupled (d) 4 (Pacific + Atlantic); (e) 5 (Atlantic-only); and (f) 6 (Pacific-only): continuous lines; and observed SSTA (dotted lines) for the period January 1962 to December 1995. Units are degrees Celsius.

the strongly damped equatorial Atlantic SSTA variability of the coupled Atlantic-only experiment 3 (Figure 2c). The latter result resembles that of a damped oscillator, reproducing previous results of *Zebiak* [1993]. The uncoupled experiment 6 using Pacific-only CCA wind stress has interannual variability, but the correlation with observations is the lowest among all the forced experiments. The results shown in Figure 2 alone suggest that the Pacific SSTA plays a role in sustaining SSTA variability over the equatorial Atlantic in the hybrid coupled model of this study. Further experiments with the Atlantic-only coupled model included some degree of additional thermodynamic forcing over the tropical Atlantic through the use of observed monthly varying cloud fraction as input to *Seager*'s [1995] AML model. However, the increased

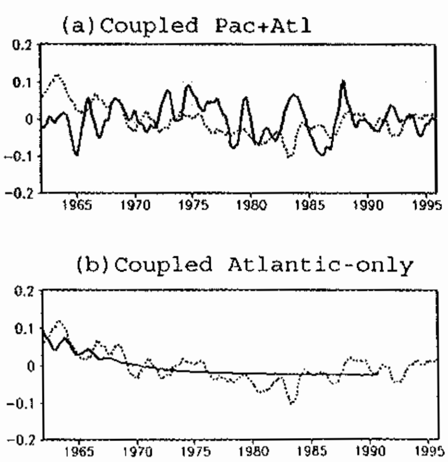

Figure 3. The same as in Figure 2, but for the zonal component of the surface wind stress for experiments (a) 2 and (b) 3 (solid line), and observations (dashed line). Units are dynes/cm^2.

SSTA variability (figures not shown) over the Atlantic was still one order of magnitude smaller than that of the forced and partially coupled experiments.

[11] Figure 3 shows the time series of area averaged zonal wind stresses over the same areas as in Figure 2, but corresponding only to experiments 2 (Figure 3a) and 3 (Figure 3b). The observed TAUXA used in forced experiment 1 is plotted as dashed lines in both panels of Figure 3. It is noteworthy in Figure 3 that the wind stress products generated by the CCA model are strongly damped for the Atlantic-only experiment (Figure 3b) and in the case of the Pacific + Atlantic model has pronounced interannual variability (Figure 3a). In fact, in the latter case the CCA TAUXA shows somewhat larger amplitude then observation. Simulated SSTA shown in Figure 2 also show larger amplitude than observations, indicating a possible systematic error of the coupled model.

[12] The ability of the coupled model to simulate SSTA variability over the tropical Atlantic is further demonstrated by the anomaly correlation maps between observed and simulated SSTA for each of the six experiments, and shown in Figure 4. Forced experiment 1 shows the best SSTA simulation over the tropical Atlantic (Figure 4a), while uncoupled experiments 4 (Figure 4d) and 5 (Figure 4e) generate best SSTA over the equatorial Atlantic. For the uncoupled Pacific-only experiment 6 (Figure 4f) the correlation are generally non-significant, except over the northern tropical Atlantic. For the coupled experiments, on the other hand, the Pacific + Atlantic experiment 2 (Figure 4b) generates marginally significant positive correlation over the western equatorial Atlantic and negative correlation over northern tropical Atlantic. The Atlantic-only coupled experiment 3 (Figure 4c) presents no significant SSTA correlation over the whole basin. This experiment has no injection of observations at all, so it cannot be expected to show any correlation unless as a prediction (which, of course, still

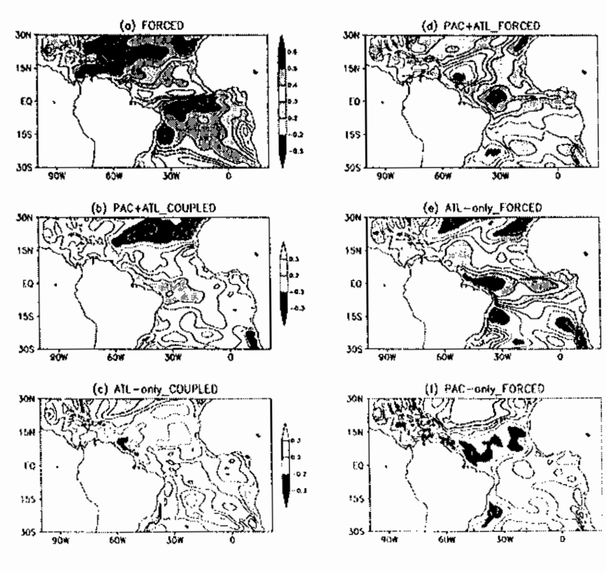

Figure 4. Anomaly correlation coefficients between observed and simulated SSTA for each of the six experiments described on Table 1: (a) Forced OGCM; coupled (b) Pacific + Atlantic; and (c) Atlantic-only; and uncoupled (d) Pacific + Atlantic, (e) Atlantic-only, and (f) Pacific-only. Shaded areas are statistically significant correlation.

couldn't be expected to have skill for more than a few months).

5. Conclusions

[13] A hybrid coupled ocean-atmosphere model of the tropical Atlantic Ocean was built to study the presence of sustained oscillations of SSTA and wind stress anomalies over the equatorial Atlantic. The forced runs of the OGCM generated SSTA time series comparable to observations. The Pacific + Atlantic and the Atlantic-only uncoupled hybrid experiment showed results which were similar to the forced experiment with observed wind stresses, but which were more confined to the equatorial region. The Pacific-only uncoupled hybrid experiment generates oscillations of SST and wind stress anomalies, but did not capture the temporal variability of SSTA over the equatorial Atlantic.

[14] While the Atlantic-only hybrid coupled model generates damped oscillations of SST and wind stress anomalies, similar to the findings of *Zebiak* [1993], the Pacific + Atlantic hybrid coupled model generates interannual variability of SST and wind stress anomalies over the equatorial Atlantic that are comparable in magnitude with observations. Yet, the fact that temporal correlation are still poor compared to forced runs suggests that other sources of forcing in the Atlantic are also important, or that our coupling processes have inadequacies.

[15] It is thus speculated that while atmospheric teleconnections between the Pacific and the Atlantic Oceans are an intrinsic component of tropical Atlantic variability, with the Pacific ENSO providing a source of disturbances necessary to maintain the otherwise damped interannual variations of SST and wind stress over the tropical Atlantic, local interactions are essential to explain the observed variability of the coupled ocean-atmosphere system over the deep tropics of the Atlantic.

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