A simple coupled model of tropical Atlantic decadal climate variability

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[1] A linear, zonally averaged model of the interaction between the tropical Atlantic (TA) atmosphere and ocean is presented. A balance between evaporation and meridional heat advection in the mixed layer determines the sea surface temperature tendency. The atmosphere is a fixed-depth, sub-cloud layer in which the specific humidity anomaly is determined by a steady-state balance between evaporation, meridional advection, and a parameterized humidity exchange with the free atmosphere. When the model is integrated, forced with observed surface wind anomalies from 1965 to the present, its simulation of the observed sea surface temperature (SST) is realistic and comparable to a simulation with a full ocean GCM. A statistical representation of surface winds and their relationship to the SST gradient across the equator is used to formulate and test a coupled model of their regional variability. Forced on both sides of the equator, in the trade-wind regions, with "white-noise" windspeed perturbations, the SST-wind relationship in the near-equatorial region feeds back positively on existing SST anomalies and gives rise to decadal variability. *INDEX TERMS:* 0312 Atmospheric Composition and Structure: Air/sea constituent fluxes (3339, 4504); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 4255 Oceanography: General: Numerical modeling. **Citation:** Kushnir, Y., R. Seager, J. Miller, and J. C. H. Chiang, A simple coupled model of tropical Atlantic decadal climate variability, *Geophys. Res. Lett.*, *29*(23), 2133, doi:10.1029/2002GL015874, 2002.

1. Introduction

[2] In the tropical Atlantic (TA), during the boreal spring, sea surface temperatures (SSTs), the inter-tropical convergence zone (ITCZ), in which the ITCZ is displaced north (south) of its climatological position when the anomalous meridional SST gradient across the equator is positive (negative) [*Hastenrath and Greischar*, 1993; *Hastenrath and Heller*, 1977; *Nobre and Shukla*, 1996; *Ruiz-Barradas et al.*, 1999].

[3] The hint of decadal oscillations displayed by this variability [*Mehta and Delworth*, 1995; *Carton*, 1996; *Rajagopalan et al.*, 1998], led to conjectures regarding an active oceanic involvement in climate within the region [*Chang et al.*, 1997; *Xie*, 1999]. However, *Seager et al.* [2001] using a hierarchy of ocean GCMs forced with observed winds, showed that it is primarily a balance between atmospheric forcing through evaporation and damping by the ocean climatological circulation, which determines TA decadal SST variability. Based on these results we propose a new simple coupled model of the evolution of zonally averaged TA SST anomalies and use it to further explore the origin of decadal variability.

2. Model Formulation

[4] Tropical Atlantic SST anomalies are well represented by zonal averages taken over the width of the basin [*Seager et al.*, 2001]. The present model simulates the evolution of such averages, between 29°S and 29°N. A mixed layer with prescribed, seasonally varying depth, and climatological currents represents the ocean, and is coupled to an atmospheric sub-cloud layer, which is a zonally averaged, linearized version of the model of *Seager et al.* [1995a].

[5] The balance governing the zonally averaged upper ocean temperature tendency, is expressed as:

$$\frac{\partial T_o'}{\partial t} = -\left(\overline{v}_o \frac{\partial T_o'}{\partial y} + \frac{\overline{w}_o T_o'}{H} + \frac{Q_{LH}'}{\rho_o C_o H}\right), \tag{1}$$

where the overbars indicate climatological means, the prime stands for anomalies, and the subscript *o* identifies the ocean variables. Here T_o is the temperature and H, v_o, and w_o are the mixed layer depth, meridional current, and upwelling velocity, respectively (all zonally averaged and functions of latitude and calendar month). The upwelling is only important on the equator [see *Seager et al.*, 2001]. The meridional current is almost symmetric around the equator, diverging poleward with a maximum rate of 5–10 cm s^{-1}, 2.5° to 10° off the equator.

[6] The latent heat flux anomaly Q_{LH}' is given by the bulk formula, linearized around the climatology:

$$Q_{LH}' = \rho_a C_E L\left(|\overline{\mathbf{u}}|(q_o' - q_a') + |\mathbf{u}'|(\overline{q}_o - \overline{q}_a)\right), \tag{2}$$

where the subscript *a* denotes an atmospheric variable, $|\mathbf{u}|$ is the surface windspeed, q the specific humidity, C_E the exchange coefficient, and L the latent heat of vaporization of water. Saturation specific humidity anomaly at sea surface temperature, q_o' is calculated from a Taylor expansion of the Clausius Clapeyron equation around the

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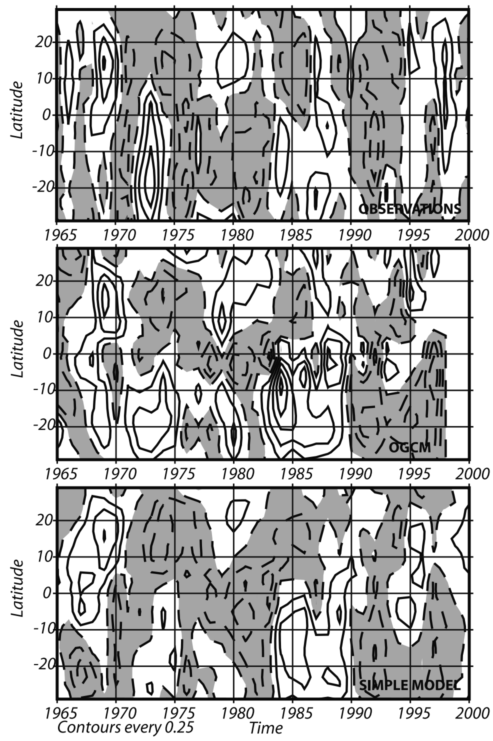

Figure 1. Annual mean SST anomaly averaged across the width of the tropical Atlantic Basin. Top: observations (from NCEP-NCAR Reanalysis). Middle: simulation by the Lamont Ocean GCM forced with observed winds [*Seager et al.*, 2001]. Bottom: simulated by the present, linear, one-dimensional model. Abscissa is in years and ordinate is latitude in degrees north. Contours are in °C every 0.25 with the zero contour omitted and negative contours dashed and shaded grey.

climatological SST value. A steady-state balance determines the specific humidity of the atmospheric mixed layer:

$$\overline{v}\frac{\partial q'_a}{\partial y} + v'_a\frac{\partial \overline{q}_a}{\partial y} = \frac{Q'_{LH}}{\rho_a L h} - \frac{C_E \mu}{h}(|\overline{\mathbf{u}}|q'_a + |\mathbf{u}'|\overline{q}_a) + \kappa\frac{\partial^2 q'_a}{\partial y^2}. \qquad (3)$$

Here v_a is the surface meridional wind (MW), h the depth (here 500 m) of the sub-cloud layer and κ the diffusion coefficient (here 0.2 10^{-7} m^2 s^{-1}). The second term on the right hand side of (3) is a linearized version of the *Seager et al.* [1995a] parameterization of the turbulent moisture exchange with the free atmosphere. In the absence of advection, the parameter μ is a function of the relative humidity [*Seager et al.*, 1995a]. We specify $\mu = 0.25$ so that, in the absence of advection, the relative humidity in the sub-cloud layer is 80%. SST damping by the atmosphere is thus determined by the physical principals entailed in the sub-cloud layer model.

[7] Equations 1–3 are solved on a 2° latitudinal grid, using a time step of one month. Zonally averaged climatological values of windspeed and MW as well as monthly anomalies of $|\mathbf{u}'|$ and v'_a are taken from observations (NCEP/NCAR Reanalysis data from 1965 to 2001). The climatological oceanic variables (meridional current and upwelling) are taken from an ocean GCM integration [*Seager et al.*, 2001]. In Figure 1 the simulated SSTs are compared to observations and to SST simulated by a three dimensional ocean GCM [*Seager et al.*, 2001]. The corresponding rms values are compared in Table 1. The simple model performs as well as the full GCM in simulating the observations. To extend it to a coupled model, the link between SST and surface winds needs to be determined.

Table 1. Root Mean Square SST Variability as a Function of Latitude

	Observations		OGCM		Linear Model	
Latitude	LF	Total	LF	Total	LF	Total
12°N to 24°N	0.245	0.344	0.257	0.361	0.264	0.306
Eq to 12°N	0.219	0.339	0.245	0.387	0.237	0.298
12°S to Eq	0.237	0.380	0.378	0.534	0.244	0.297
24°S to 24°N	0.261	0.407	0.430	0.517	0.258	0.294

LF stands for the low-frequency part of the variability (filtered with a 3 yr cutoff). **Total** stands for the full spectrum of the variability (monthly resolution). **Linear Model** refers to the model of the present study forced with observed, zonally averaged, monthly wind anomalies. Data are for 1965–2000.

3. The Year-Round Relationship Between Winds and SST in the Tropical Atlantic

[8] The fundamental pattern of atmosphere-ocean relationship in the TA is revealed by a leading EOF of combined, zonally averaged, SST, windspeed, and MW in the region (Figure 2). The SST anomaly in the Northern Hemisphere trade region, begins forming in December, reaches its peak in March–May, and decays by the end of the boreal summer (Figure 2, left panel). The corresponding trade windspeed anomaly starts in December, peaks in

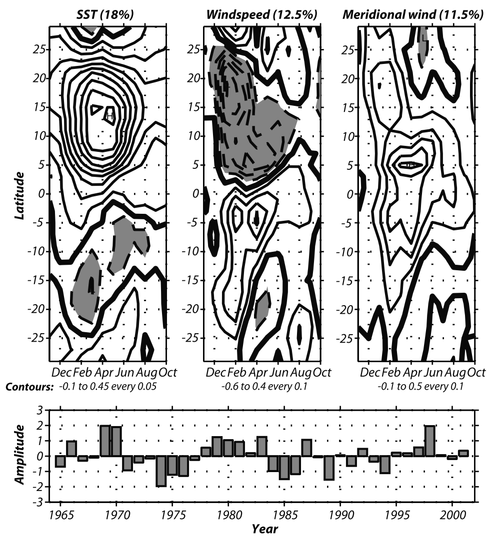

Figure 2. Leading EOF of combined tropical Atlantic SST (°C), windspeed and meridional wind (both in m s^{-1}), averaged across the width of the basin and arranged in yearly samples of latitude-by-calendar month. Data are from November 1964 to October 2001. Negative contours dashed and shaded. The contour intervals are indicated below each panel. Percent variance explained in each field is shown in parentheses above. The time series corresponding to the combined EOF is shown below, one value for each year of the corresponding January.

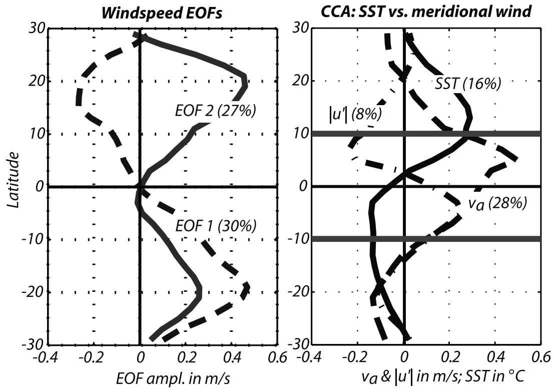

Figure 3. Left panel: The two leading EOFs of monthly windspeed data, 1965–2001. Right panel: the leading pattern emerging from a canonical correlation analysis between monthly SST (solid line) and meridional wind (heavy dashed line) data, 1965–2001. Also shown on the right is the projection of windspeed onto the first canonical correlation time series of SST/wind (dashed-dotted line). Abscissa is in m/s and °C and ordinate is latitude in degrees north. Percent variance explained by each pattern is given in the parentheses. The horizontal lines at 10° N and S on the right, indicate where the windspeed pattern was truncated to simulate an equatorially confined SST-wind feedback.

January, and declines in March–April (Figure 2 middle panel). Thus a warming of the local SST follows a weakening in the strength of the trades. This is consistent with the idea that trade-region SST anomalies are driven by surface fluxes [see also *Czaja et al.*, 2002]. Two secondary windspeed extremes occur closer to the equator (~ 5°N and S) in spring, when the SST anomaly reaches its peak value. These are associated with the largest MW perturbation (Figure 2, right panel), such that a weakening of wind speed north of the equator and a strengthening to the south, correspond to an anomalous northward flow centered on 5°N. This relationship is in agreement with the two dimensional pattern of surface wind anomaly [*Nobre and Shukla*, 1996]. The temporal evolution of the winds in the near-equatorial region is consistent with the notion that the cross-equatorial flow responds to SST anomalies north of the equator and the associated change in windspeed suggests a positive evaporation-SST feedback near the equator [c.f., *Chang et al.*, 2000; *Sutton et al.*, 2000; *Chiang et al.*, 2002].

[9] To couple the winds to the SST field, we take the view that random, or externally forced trade wind variability creates large-scale SST variability, which invoke a near-equatorial wind response. Using observed, year-round, zonally averaged, monthly anomalies of SST windspeed and MW, we find that the trade-region forcing is captured by the two leading EOFs of windspeed, which peak at 20° S and N (Figure 3, left panel). The relationship between anomalous SST and MW is captured by the leading pattern of a canonical correlation analysis [CCA, *Barnett and Preisendorfer*, 1987], which depicts the coupling between the latitudinal SST gradient and the cross equatorial MW perturbation (Figure 3, right panel). The corresponding pattern in windspeed is determined by projecting monthly windspeed anomalies on the MW canonical time series

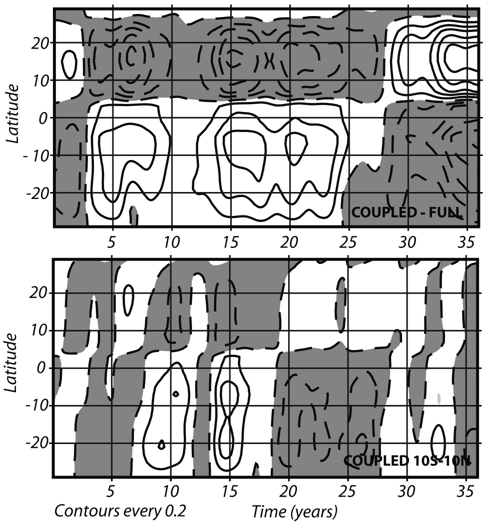

Figure 4. Top panel: a simulation of SST with the linear, one-dimensional, statistically coupled model, forced with the first two EOFs of windspeed with "white noise" time amplitudes and with the meridional wind coupled via CCA analysis to the SST field. Bottom panel: a similar simulation but with the meridional wind - SST coupling confined to 10° latitude north and south of the equator. The monthly data were low-pass filtered before plotting to eliminate fluctuations with periods less than 3 years. Contours every 0.2°C, negative contours are dashed and shaded grey. Zero contours are omitted. Abscissa is time in years since the start of the integration.

(Figure 3, right). The pattern peaks at about 5°N and S, away from the peaks in the windspeed EOFs, but its influence over the latter is not negligible.

4. Testing a Statistically Coupled Model of Tropical Atlantic Decadal Variability

[10] The *coupled model* consists of the linear, one-dimensional system described in section 2 and the statistical SST-wind relationship described above. Forcing is applied month-by-month by specifying the time amplitudes of the two trade-windspeed EOFs (Figure 3, left). The feedback is determined by projecting the evolving SST anomaly on the SST CCA pattern (Figure 3, right), deriving the near-equatorial MW and windspeed response appropriately (Fig-

Table 2. Root Mean Square SST Variability as a Function of Latitude as Simulated by the Statistically Coupled Model of the Present Study

	No Taper		With Taper		No Coupling	
Latitude	LF	Total	LF	Total	LF	Total
12°N to 24°N	0.404	0.408	0.128	0.170	0.122	0.169
Eq to 12°N	0.258	0.261	0.091	0.120	0.054	0.085
12°S to Eq	0.358	0.360	0.128	0.146	0.060	0.080
24°S to 24°N	0.288	0.292	0.155	0.192	0.145	0.182

LF and Total as in Table 1. Results are based on a 500-year simulation with "white noise" amplitudes applied to the forcing windspeed EOFs. The taper was applied to the SST-wind coupling pattern to confine it to the 10°S–10°N belt. In the "no coupling" run the CCA SST-wind coupling was turned off entirely.

ure 3, right), and adding the result to the wind field in the next time step.

[11] When forcing the model with the two windspeed EOFs, with amplitudes drawn from a Gaussian "white noise" process, the SST response (Figure 4, top panel) displays considerable multi-year variability, which is an exaggerated version (in both amplitude and duration) of the uncoupled simulation (Figure 1, bottom panel). This suggests that the near-equatorial SST-wind coupling, with its positive flux-SST feedback, is causing the multi-year variability in the trade regions. Confining the extent of the near-equatorial SST-wind coupling to the latitude belt 10°S – 10°N (see Figure 3, right) markedly reduces the strength of multi-year SST variability but its presence still is discernible (Figure 4, bottom panel). Eliminating the SST-wind coupling altogether further reduces the low-frequency SST variability (not shown).

[12] In Table 2 the simulated total and decadal, rms SST variability in a 500-year integration of the randomly forced, coupled model is presented. The amplitude of SST fluctuations in the decadal band is sensitive to the latitudinal extent of the MW feedback. When limiting the latter to the near-equatorial region the amplitude is greatly reduced, particularly in the northeasterly trades region, but it is larger than when the feedback is turned off completely. The effect of the feedback is unambiguous in the near-equatorial region. The coupled SST spectrum does not display any periodic oscillation but rather a noticeable reddening of the spectrum (not shown).

5. Summary and Conclusions

[13] In the two previous attempts to simulate TA variability with simplified models, decadal oscillations emerged due to either a slow cross-equatorial oceanic advection of the SST anomalies [*Chang et al.*, 1997] or SST advection by Ekman currents forced by trade wind anomalies [*Xie*, 1999]. Here the ocean plays only a damping role and cannot advect anomalies across the equator (due to the characteristic of the prescribed current), or within the trade region (because anomalous Ekman currents are neglected following *Seager et al.* [2001]). The long time scales are merely the result of a weak positive flux-SST feedback that "leaks" into the trade regions and interferes with the random forcing there.

[14] The strength of the low-frequency SST variability depends on the latitudinal extent of the near-equatorial coupling effect. This cannot be determined from a statistical analysis of observed data and needs to be explored with a dynamical model. A recent coupled model experiment with a full GCM seems to justify the assertion that the feedback extends well into the trade regions and affects the character of the regional SST variability [*Okumura et al.*, 2001]. Thus, it appears that the positive SST-wind feedback in the equatorial Atlantic is capable of modifying random internal or external forcing and needs to be considered in the climate variability of this region.

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