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A pan-Atlantic decadal climate oscillation

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Abstract. Sea surface temperature (SST) variabilities on time scales of 10-14 years have been documented in various parts of the Atlantic Ocean. Here we present observational evidence that these regional variabilities are part of a coherent pan-Atlantic decadal oscillation (PADO) characterized by zonal bands of SST and wind anomalies stacked in the meridional direction with alternate polarities from the South Atlantic all the way to Greenland. We propose that the interaction of wind, evaporation and SST is key to establishing this interhemispherical PADO, based on results from a new ocean-atmosphere coupling model. Forced by extratropical wind forcing, the model successfully reproduces the observed decadal oscillation in both SST and wind velocity over the Tropics. This decadal extratropical forcing of the Tropics is in sharp contrast to the well-known Tropics-to-extratropics teleconnection that operates on interannual time scales in association with El Nino/Southern Oscillation (ENSO).

1. Observational Background

The SST distribution over the Atlantic exerts a great influence on the climate and its variability over the surrounding continents. Particularly rainfall variability in the Sahel (Lamb 1978) and Northeast Brazil (Hastenrath and Heller 1977) is associated with a dipole pattern of SST anomaly with opposing polarities north and south of the intertropical convergence zone (ITCZ). Figure 1b shows a dipole index defined by Servain (1991) that oscillates on decadal time scales. Figure 1a is a composite map of this tropical decadal oscillation (TDO). Regression based on the full time series yields a similar anomaly pattern (not shown).

A positive feedback of wind speed, evaporation and SST (WES; Xie and Philander 1994) seems at work in the Tropics: The contrast between positive SST anomalies to the north and negative ones to the south of the equator induces cross-equatorial southerly winds, which veer under the Coriolis force and attain a westerly (easterly) component in the Northern (Southern) Hemisphere. Superimposed on the mean easterly trade winds, these zonal wind anomalies reduce (increase) wind speed north (south) of the equator, reinforcing the initial south-to-north SST gradient through surface evaporation. Semi-empirical (Chang et al. 1997) and dynamic (Xie 1998) ocean-atmosphere models incorporating this WES feedback produce decadal oscillations resembling the observed TDO.

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Previous studies of SST variability tend to divide the Atlantic Ocean into the northern (Kushnir 1994), tropical (Mehta and Delworth 1995; Nobre and Shukla 1996) and southern (Venegas et al. 1997) parts and focus on one of these subdomains. Here we take an ocean-scale view and extend our composite procedure to the whole Atlantic basin. The TDO-based composite anomalies are not confined to the Tropics, with centers of action stacked all the way into high-latitude North Atlantic (Fig. 1a). The SST anomaly center off Newfoundland has been previously identified (Deser and Blackmon 1993) and is associated with change in the strength of the prevalent westerly winds. This North Atlantic decadal oscillation (NADO) varies in phase with the TDO (Fig. 1b). Another SST anomaly center lies off the east coast of the United States. Sutton and Allen (1997) suggest that this anomaly center is not spatially stationary but propagates northeastward along the Gulf Stream and North Atlantic Current. The extratropical wind anomalies are characterized by an anti-cyclonic circulation in the high latitudes and a cyclonic one between 20N and 40N, indicating that the atmospheric North Atlantic Oscillation (NAO)—the seesaw between the Icelandic low and the Azores high (Hurrel 1995) —is part of the pan-Atlantic decadal oscillation (PADO).

It remains controversial how to characterize tropical Atlantic SST variability. Principal component (PC) analyses yield an interannual monopole and a decadal dipole mode whereas rotated PCs are uncorrelated between the hemispheres (Houghton and Tourre 1992). While it is difficult at this time to resolve this controversy solely from a statistical point of view given the limited length of data, theoretical studies suggest the existence of a dipole mode astride the equator (Chang et al. 1997; Xie 1998). Indeed equatorially symmetric and anti-symmetric instabilities emerge as independent modes in a linear coupled model (Noguchi 1998). Further studies with longer data records and coupled GCM experiments are needed to settle this issue. The PADO described above, however, is not sensitive to the choice of decadal oscillation index. Independent regression analyses based on an NAO index yield a similar pan-Atlantic SST anomaly pattern (M. Watanabe and T. Nitta 1997; Y. Kushnir 1998, both personal communications).

2. Model

To investigate the linkage between the Tropics and extratropics in the PADO, we use a linear dynamic ocean-atmosphere model (Xie 1998). The model is zonally averaged to emphasize the interaction in the meridional direction and covers an ocean domain extending from 30S to 30N. SST perturbations (T) are caused by evaporation changes and advected by surface Ekman velocity (v):

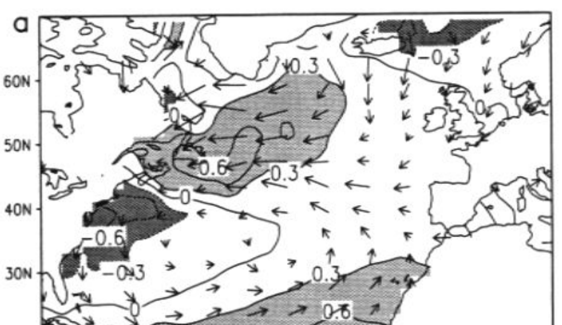

Figure 1. **a**, Annual-average SST (°C) and wind velocity (m/s) anomalies associated with the PADO, defined as the difference between six high (1969, 70, 78, 80, 81 & 92) and six low (1972, 73, 74, 84, 85 & 86) TDO-index years. **b**, upper line: Zonal-mean SST anomalies averaged between 43N-53N (offset by 0.7°C); lower lines: Observed (thick) and simulated (thin) TDO indices defined as the SST difference between 10N-20N and 15S-5S. Annual-means are first constructed from the Comprehensive Ocean-Atmosphere Dataset (Woodruff et al. 1987) and then smoothed by taking three-point running mean to filter out high-frequency variability in **b**. Missing data are not filled.

$$T_t + \overline{v}T_y + v\overline{T}_y = aU - bT + \kappa T_{yy}$$

where κ is the diffusivity, the subscript denotes partial derivative and the overbar the climatological mean. Following Xie (1997), evaporation is broken into two terms: the Newtonian cooling with coefficient b and a wind speed (U) dependent one with WES coefficient a. Vertical advection is unimportant because mean downwelling dominates the off-equatorial Tropics where TDO's centers of action are located. Forced by observed wind speed, this ocean model successfully simulates the observed TDO (thin line in Fig. 1b). Its simulation skill is comparable to that of a state-of-the-art Atlantic GCM (Carton et al. 1996), giving us some confidence in the usefulness of the model.

A regression analysis based on the TDO index indicates that negative sea level pressure (SLP) anomalies are associated with positive SST anomalies over the tropical Atlantic (Tanimoto and Xie 1998). These SLP anomalies are likely due to SST-induced temperature changes in the planetary boundary layer. We hence use the Lindzen and Nigam (1987) model to represent this atmospheric response and compute wind anomalies.

3. Results

No self-sustaining oscillation is found in the coupled model with $b=b_0=(1\ \text{year})^{-1}$, a rate arising from the temperature dependence of surface evaporation and being the lower limit for realistic SST damping. We then force the coupled model with "weather" noises confined to the extratropics poleward of 20°. The forcing functions in the southern and northern extratropics both have a white-noise spectrum but are mutually uncorrelated (Fig. 2b). The tropical ocean-atmosphere system apparently chooses to respond only to anti-symmetric part of the forcing (Fig. 2c). Pronounced low-frequency SST anomalies anti-symmetric about the equator dominates the Tropics between 20S and 20N, a region free of external forcing (Fig. 2a). The centers of the SST dipole are located around 15° in agreement with observations. The WES feedback, manifested by the in-phase relation between zonal wind and SST (Fig. 3), maintains this coherent dipolar structure. Wind anomalies associated with the tropical dipole extend into the extratropics where they appear negatively correlated between the hemispheres.

Equatorward propagating SST perturbations are visible poleward of 20°, another consequence of the WES feedback (Xie 1997; Carton 1997). Over a positive SST anomaly in the Northern Hemisphere (Fig. 3), a low pressure forms with westerly (easterly) wind anomalies to the south (north). If the climatological mean wind is easterly as in the tropical Atlantic, total wind speed and hence evaporative cooling decrease (increase) south (north) of the original SST anomaly, causing it to move toward the equator. By this mechanism, extratropical signals are transmitted into the Tropics, causing the stationary dipole to oscillate.

If the Newtonian cooling rate is set to zero (b=0), an unstable mode with a dipolar structure similar to that in Fig. 2a dominates the model and oscillates due to the aforementioned phase difference between SST and wind perturbations. Poleward Ekman flows driven by the mean easterly winds slow the equatorward phase propagation and hence the oscillation (Xie 1998). With a small growth rate (e-folding time: 2 years), this free mode does not survive the Newtonian damping (b_0^{-1}=1 year). Nevertheless, as the least damped mode it can be readily excited by extratropical forcing with a projection onto its modal structure. This is illustrated by a weakly damped case (dotted line in Fig. 2d) where the model response to white noise forcing displays a resonance spectral peak at the free mode's frequency ($2\pi/f_0$=11.5 years). However, the spectrum is red under realistic damping ($b/b_0>1$) suggesting that any preferred time scales are not due to tropical processes alone but must come from the extratropics. Like a damped harmonic oscillator under forcing, the spectral power falls rapidly for $f>f_0$, indicating that the WES feedback acts as a low-pass filter

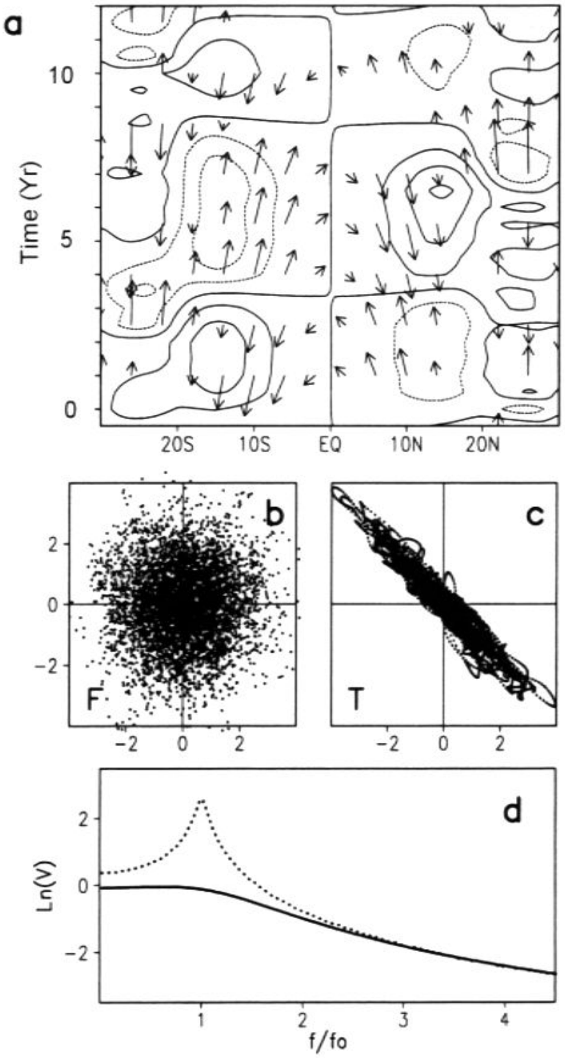

Figure 2. **a**, Latitude-time section of SST anomaly (negative dashed; contour interval: 0.75°C) in a coupled ocean-atmosphere model ($b=b_0$) forced by extratropical white-noise wind disturbances. The forcing has a fixed spatial structure reaching a maximum at 30° and vanishing at 20°. Anomalous wind velocity (ms^{-1}) is plotted with an upleft vector denoting southeasterly wind. Scatter plots of **b**, white-noise forcings applied to the northern and southern extratropics and **c**, model SSTs at 15N and 15S (All data are normalized with their variances). **d**, Spectra of meridional wind velocity (V) at the equator calculated from 500-year integrations with weak ($b=0.6b_0$; dotted) and realistic ($b=b_0$; solid line) damping rates. Wind velocity is normalized by forcing amplitude and frequency by that of the leading WES mode, f_0 with $2\pi/f_0$ =11.5 years.

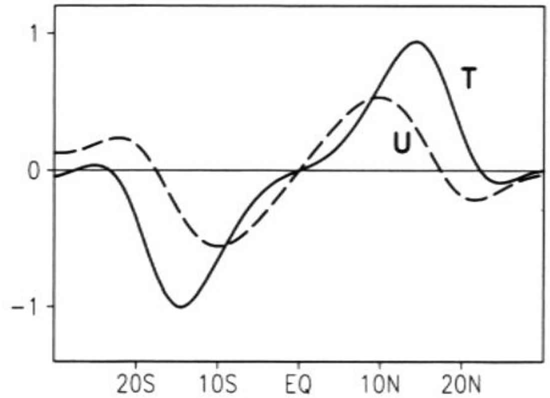

Figure 3. SST (°C; solid) and zonal wind velocity (ms^{-1}; dashed line) regressions onto -SST (y=15 °S) based on 200-year model outputs.

allowing decadal or longer extratropical signals into the Tropics but not interannual ones.

To further demonstrate that the extratropical variability dictates the Atlantic TDO, we conduct a coupled model simulation where the extratropics poleward of 20N/S is forced by observed winds while the Tropics are free of forcing. As the model does not respond to high-frequency forcing, annual mean winds are used to increase the number of available observations. Figure 4 compares simulated and observed TDO indices. Our coupled model successfully simulates the observed TDO, capturing the two and half cycles since 1960 when the number of data becomes sufficient for a meaningful simulation. We note that the TDO becomes very pronounced after 1970, coinciding with a period when marked equatorward-propagating anomalies from the North Atlantic are observed (Halliwell 1997; Tanimoto and Xie 1998).

4. Discussion

Our analysis of historic data reveals a coherent decadal oscillation that spans the whole Atlantic Ocean from 30S to 70N. The origin of this PADO is unclear yet. As the Tropics does not favor any particular time scale, the North Atlantic seems key to producing the preferred decadal time scale. Possible causes of the NADO include instabilities of the thermohaline circulation (Weaver and Sarachik 1991),

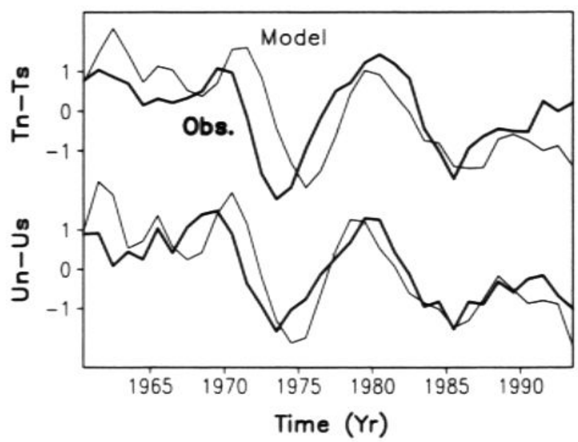

Figure 4. Observed (thick) and simulated (thin lines) hemispheric differences in SST (upper) and zonal wind speed (lower panel) between 10N-20N and 20S-10S. (All the curves are normalized with their respective variances and a three-year running mean is applied to the observed data). Note that the model data are taken from regions free of external forcing.

outflow of arctic ice (Dickson et al. 1988) and local air-sea interaction (Latif and Barnett 1994). The Azores high pressure system extends into the mean easterly wind regime and could provide the forcing for the TDO as it oscillates with the NAO. In response to extratropical variability, the Tropics produces a dipole pattern linking the two hemispheres. The tropical SST anomalies so produced can feed back onto the extratropics via atmospheric teleconnection (Wallace et al. 1990; D. Battisti 1996, personal communication). The paucity of data prevents us from obtaining robust results south of 30S, but Venegas et al.'s (1997) first mode displays a dipolar SST pattern between the tropical and extratropical South Atlantic and its time series resembles that of the TDO index in Fig. 1b. If the TDO-forced atmospheric waves extend into both the North and South Atlantic, they could provide a mechanism to synchronize the decadal oscillation over the whole Atlantic Ocean.

The ENSO in the equatorial Pacific is the major source of variability on interannual time scales, affecting the global climate via atmospheric teleconnections (Tanitomo et al. 1993; Lau 1997). A two-tiered system is therefore successful in predicting interannual variability (Bengtsson et al. 1994), in which tropical SST prediction is first produced and then used to drive an atmospheric GCM for global forecasts. Decadal prediction seems to require a different approach with the extratropics—the North Atlantic in particular—taking an active key role. Our results have a further implication for paleoclimatological research. Given that the WES mode responds strongly to extratropical forcing on time scales decadal and longer, it will be interesting to correlate sequences of climate proxies at these centers of action in Fig. 1a and see if the same PADO emerges on other longer time scales.

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References

Bengtsson, L. et al., A two-tiered approach to long-range climate forecasting. *Science*, **261**, 1026-1029, 1994.

Carton, J.A., See-saw sea. *Nature*, **385**, 487-488, 1997.

Carton, J., X. Cao, B.S. Giese and A.M. da Silva, Decadal and interannual SST variability in the tropical Atlantic Ocean. *J. Phys. Oceanogr.*, **26**, 1165-1175, 1996.

Chang, P., L. Ji and H. Li, A decadal climate variation in the tropical Atlantic ocean from thermodynamic air-sea interactions. *Nature*, **385**, 516-518, 1997.

Deser, C. and M.L. Blackmon, Surface climate variations over the North Atlantic Ocean during winter. *J. Clim.*, **6** 1743-1753, 1994.

Dickson, R.R., J. Meincke, S.A. Malmberg and A.J. Lee, The "great salinity anomaly" in the northern North Atlantic 1968-1982. *Prog. Oceanogr.*, **20**, 103-151, 1988.

Halliwell, G.R., Jr., Decadal and multidecadal North Atlantic SST anomalies driven by standing and propagating basin-scale atmospheric anomalies. *J. Clim.*, **10**, 2405-2411, 1997.

Hasternrath, S. and L. Heller, Dynamics of climatic hazards in northeast Brazil. *Q. J. Roy. Meteor. Soc.*, **110**, 77-92, 1977.

Houghton, R.W. and Y.M. Tourre, Characteristics of low-frequency sea surface temperature fluctuations in the tropical Atlantic. *J. Clim.*, **5**, 765-771, 1992.

Hurrell, J.W., Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science*, **269**, 676-679, 1995.

Kushnir, Y., Interdecadal variation in North Atlantic sea surface temperature and associated atmospheric conditions. *J. Clim.*, **7**, 141-157, 1994.

Lamb, P.J., Large-scale tropical Atlantic surface circulation patterns associated with subsahara weather anomalies. *Tellus*, **30**, 240-251, 1978.

Latif, M., and T.P. Barnett, Causes of decadal climate variability over the North Pacific and North America. *Science*, **266**, 634-637, 1994.

Lau, N.-C., Interactions between global SST anomalies and the midlatitude atmospheric circulation. *Bull. Amer. Met. Soc.*, **78**, 21-33, 1997.

Lindzen, R.S. and S. Nigam, On the role of sea surface temperature gradients in forcing low level winds and convergence in the tropics. *J. Atmos. Sci.*, **44**, 2418-2436, 1987.

Mehta, V.M. and T. Delworth, Decadal variability of the tropical Atlantic ocean surface temperature in shipboard measurements and in a global ocean-atmosphere model. *J. Clim.*, **8**, 172-190, 1995.

Nobre, P. and J. Shukla, Variations of sea surface temperature, wind stress, and rainfall over the tropical Atlantic and South America. *J. Clim.*, **9**, 2464-2479, 1996.

Noguchi, H., *Coupled ocean-atmosphere instabilities by wind-evaporation-SST feedback.* M.Sc. Thesis, Hokkaido University, Sapporo, Japan, 1998.

Sutton, R.T. and M.R. Allen, Decadal predictability of North Atlantic sea surface temperature and climate. *Nature*, **388**, 563-567, 1997.

Tanimoto, Y., N. Iwasaka and K. Hanawa, Characteristic variation of sea surface temperature with multiple time scales in the North Pacific. *J. Clim.*, **6**, 1153-1160, 1993.

Tanimoto, Y. and S.-P. Xie, Ocean-atmospheric variability over the pan-Atlantic basin. *J. Meteor. Soc. Japan*, submitted, 1998.

Venegas, S.A., L.A. Mysak and D.N. Straub, Atmosphere-ocean coupled variability in the South Atlantic. *J. Clim.*, **10**, 2904-2920, 1997.

Wallace, J.M., C. Smith and Q.-R. Jiang, Spatial patterns of atmosphere/ocean interaction in the northern winter. *J. Clim.*, **3**, 990-998, 1990.

Weaver, A.J. and E.S. Sarachik, Evidence for decadal variability in an ocean general circulation model: An advective mechanism. *Atmos.-Ocean*, **29**, 197-231, 1991.

Woodruff, S.D., R.J. Slutz, R.L. Jenne and P.M. Steurer, A comprehensive ocean-atmosphere dataset. *Bull. Amer. Met. Soc.*, **68**, 521-527, 1987.

Xie, S.-P., A dynamic ocean-atmosphere model of the tropical Atlantic decadal variability. *J. Clim.*, **11**, in press, 1998.

Xie, S.-P., Unstable transition of the tropical climate to an equatorially asymmetric state in a coupled ocean-atmosphere model. *Mon. Wea. Rev.*, **125**, 667-679, 1997.

Xie, S.-P. and S.G.H. Philander, A coupled ocean-atmosphere model of relevance to the ITCZ in the eastern Pacific. *Tellus*, **46A**, 340-350, 1994.

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