The Low-Frequency Variability of the Tropical Atlantic Ocean

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ABSTRACT

Upper-ocean temperature variability in the tropical Atlantic is examined from the Comprehensive Ocean–Atmosphere Data Set (COADS) as well as from an ocean model simulation forced by COADS anomalies appended to a monthly climatology. The findings are as follows: Only the sea surface temperatures (SST) in the northern Tropics are driven by heat fluxes, while the southern tropical variability arises from wind-driven ocean circulation changes. The subsurface temperatures in the northern and southern Tropics are found to have a strong linkage to buoyancy forcing changes in the northern North Atlantic. Evidence for Kelvin-like boundary wave propagation from the high latitudes is presented from the model simulation. This extratropical influence is associated with wintertime North Atlantic oscillation (NAO) forcing and manifests itself in the northern and southern tropical temperature anomalies of the same sign at depths of 100–200 m as result of a Rossby wave propagation away from the eastern boundary in the wake of the boundary wave passage. The most apparent association of the southern tropical sea surface temperature anomalies (SSTA) arises with the anomalous cross-equatorial winds that can be related to both NAO and the remote influence from the Pacific equatorial region. These teleconnections are seasonal, so that the NAO impact on the tropical SST is the largest at midwinter but in spring and early summer the Pacific remote influence competes with NAO. However, NAO appears to have a more substantial role than the Pacific influence at low frequencies during the last 50 years. The dynamic origin of SSTA is indirectly confirmed from the SST–heat flux relationship using ocean model experiments that remove either anomalous wind stress forcing or atmospheric forcing anomalies contributing to heat exchange.

1. Introduction

Variability of the tropical Atlantic has been of wide interest due to its relationship to rainfall in the surrounding landmasses, primarily northeastern Brazil (Nordeste), Sahel, and Angola, Africa (Hastenrath 1978; Moura and Shukla 1981; Folland et al. 1986; Hirst and Hastenrath 1983). These climatic conditions are associated with a dipole of SST anomalies in the Tropics that is the second empirical orthogonal function (EOF) of SST anomalies (Hastenrath 1978; Houghton and Tourre 1992). The existence of this dipole pattern has been questioned (Houghton and Tourre 1992; Enfield and Mayer 1997; Enfield et al. 1999) because the two centers are not anticorrelated with each other at zero lag.

This work will explore the dynamical origin of the decadal variability in the tropical Atlantic Ocean. So far the studies are inconclusive as to whether the decadal variability is internal to the Tropics (Chang et al. 1997) arising from so-called wind–evaporation–SST feedback (Xie and Philander 1994), or driven remotely by the Pacific, or related to the extratropical North Atlantic, or whether a well-defined ''decadal'' signal in the Atlantic exists at all (Dommenget and Latif 2000). The study by Tourre et al. (1999) finds a tropical–extratropical oscillatory mode with a period of 11.4 yr that displays a tropical dipole as a part of a joint sea level pressure (SLP) and SST pattern. The SLP pattern associated with their decadal mode resembles the North Atlantic oscillation (NAO). Rajagopalan et al. (1998) found a significant association with NAO and tropical variability at decadal timescales, but arrived at an opposite conclusion by suggesting that the decadal variability is internal to the Tropics. Based on model experiments, Xie and Tanimoto (1998) and Tanimoto and Xie (1999) suggest that the tropical low-frequency variability is likely to derive from extratropical forcing.

The key element in resolving any of the issues related to the tropical decadal variability is to identify the atmospheric forcing associated with the decadal SST anomalies. Tanimoto and Xie (1999) show that a NAO-like SLP pattern dominates the North Atlantic when the tropical north–south temperature gradient has extreme values. The heat flux associated with NAO has three centers of action: subpolar gyre, western subtropics (20°–40°N), and eastern North Atlantic (5°–25°N) off the African coast (Cayan 1992), which are also the centers of the leading EOF mode for surface heat flux (Häkkinen 1999). The center off the African coast coincides with the area of the tropical dipole, and thus a natural linkage between the northern Tropics and NAO exists. The role of local heat flux as a source of northern tropical SST anomalies has been discussed by Carton et al. (1996) and Enfield and Mayer (1997). However, the forcing of southern tropical SST anomalies appear to be problematic. Enfield and Mayer (1997) could not find

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any relationship to heat flux while Chang et al. (1997) could construct empirical modes for joint SST–heat flux variability involving both the southern and northern Tropics.

Since heat flux forcing may not be the leading cause of the southern tropical anomalies, we have to explore the role of ocean circulation changes, either driven by local wind stress or remotely forced. One such candidate is the meridional wind variability that appears to be strongly correlated with southern tropical SST anomalies (Bojariu 1997). The work of Philander and Pacanowski (1981a) shows that southerly winds set up a shallow equatorial cell with southerly flow at the surface and northerly flow at subsurface. This cell is associated with upwelling in the southern side and downwelling in the northern side. They also suggest that the southerly winds are responsible for the temperature distribution of the tropical Atlantic where a cold tongue is found in the southeast (SE) sector of the Tropics in an equilibrium state (in a viscous fluid). The other candidate for tropical SST anomalies is the thermohaline circulation that would mainly influence the subsurface temperatures.

Our objective is to study the relationship between the heat flux, wind stress, SST, and upper-ocean temperature anomalies in the Atlantic Tropics. Furthermore we will examine how the SST anomalies in the tropical Atlantic relate to the extratropical ocean, NAO, and the variability in the equatorial Pacific. Analyses are done for SST and atmospheric data based on the Comprehensive Ocean–Atmosphere Response Experiment (COADS; daSilva et al. 1994), which have been used to simulate the oceanic variability from 1946 to 1993. All results from COADS were cross validated by the 51-yr dataset from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis.

We will show that the southern tropical SST anomalies are closely linked to the northern tropical subsurface anomalies even though the SST anomalies on either side of the equator are not correlated. This linkage is achieved through the NAO influence, where the subsurface signal propagates from high latitudes to the Tropics. Secondly we will show that SST in the Atlantic Tropics is influenced by the Pacific low-frequency variability. The Pacific and NAO impact on the southern SST takes place mainly through a dynamic adjustment to meridional wind stress anomalies in the central equatorial region, but in the northern Tropics the SST anomalies are driven by local heat flux. The NAO and Pacific impact are not completely separated seasonally, and since SST anomalies can persist for several months, the influence of the two forcings compete in the surface signal. The contents are divided so that the observational and model-simulated datasets along with the ocean model and its forcing, are discussed in section 2. The comparison of observed and simulated SST is presented in section 3a. The variability of the simulated oceanic anomalies in the upper 200 m are discussed in section 3b. The forcing of the northern and southern SST anomalies are considered in section 4. Section 5 presents a summary of interactions between the northern and southern Tropics in the Atlantic.

6. Discussion

The Atlantic upper-ocean temperature variability is studied from COADS observations and from an ocean model simulation forced by COADS anomalies appended to a monthly climatology. The starting point of this study is the SST–heat flux relationship: we find that in the northern Tropics the heat flux anomalies force the temperature anomalies, but in the southern Tropics the relationship between the heat flux and temperature anomalies is neutral, and closer to the equator a weak damping is evident. A comparison with a model experiment without wind stress anomalies but retaining atmospheric anomalies contributing to surface heat exchange shows that the southern tropical SST anomalies would be forced by the local atmosphere as opposed to being neutral or damped as in the full simulation (also in the COADS data). This behavior is consistent with a strong coupling between the atmosphere and the ocean, where SSTA practically drives the atmospheric temperature anomalies. The difference in the surface heat exchange between the two experiments suggests that the southern anomalies have to arise from other processes such as wind-driven circulation changes. Our study suggests that the initial appearance of SSTA in the southern Tropics is a forced response to ocean circulation changes, but does not exclude the possibility of a subsequent atmospheric response as put forward in Robertson et al. (2000).

Specifically the low-frequency southern tropical SST variability is found to be tied to the cross-equatorial wind stress. Based on Philander and Pacanowski (1981a) the meridional wind stress in the Tropics leads to a shallow overturning cell at the equator and pycnocline changes along the boundaries such that southerly winds would cause a strong cold tongue in the eastern southern Tropics. Analogous to this, the northerly wind stress component would lead to deeper pycnocline and warm SST anomalies in the STA region. The significance of the meridional wind component has been brought up by Bojariu (1997) in search of connections between NAO and the tropical variability. We find a connection between NAO and STA that is quite specific to the boreal winter season and that during spring–early summer the Pacific remote forcing is also associated with STA, again through a meridional wind stress signal at the equator.

This difference in the dynamic origin of the northern and southern variability is limited to the surface. At the subsurface (at 100 m and below) the model results show that temperature anomalies of the same sign exist on both sides of the equator. This in-phase relationship is expected from the studies of oceanic adjustment to high-latitude buoyancy forcing that would give rise to equatorward-propagating boundary waves, transforming into equatorial Kelvin waves along the equator and branching into both hemispheres on the eastern boundary and generating westward-propagating Rossby waves in their wake (Wajsowicz 1986; Kawase 1987). The wave dynamics of the extratropical origin determine that the anomalies at depth on both sides of the equator are of the same sign.