9.8 THE INTERANNUAL VARIABILITY IN THE TROPICAL ATLANTIC OCEAN SIMULATED BY A REGIONALLY COUPLED OCEAN-ATMOSPHERE GCM

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1. INTRODUCTION

There exists the systematic interannual and decadal variability in the tropical Atlantic Ocean that significantly affects the regional climate variations (Huang and Shukla 1997). For instance, an anomalous "dipole pattern" of the sea surface temperature (SST) straddling the climatological position of the inter-tropical convergence zone (ITCZ) is closely associated with abnormally dry and wet years in northeast Brazil (e.g., Moura and Shukla 1981) and sub-Saharan Africa (e.g., Lamb and Pepler 1991). On the other hand, SST anomalies in the equatorial and southeast ocean cause rainfall fluctuations in the Gulf of Guinea and the southeastern coastal regions. An understanding of the mechanisms of the tropical Atlantic variability should improve our ability to forecast the regional climate on seasonal, interannual, and even decadal time scales.

Previous studies have identified several factors that cause the SST anomalies in the tropical Atlantic Ocean. One is the ocean-atmosphere coupling within the tropical Atlantic sector. The main regional air-sea interaction seems to be a positive feedback among the fluctuations of the surface wind speed, evaporative heat loss, and SST (Chang et al., 1997), causing the low-frequency variability of the merdional SST gradient and the overlying atmospheric circulation. Around the equator, the surface wind stress, SST, and the thermocline also co-vary in a fashion somewhat similar to that of El Niño/Southern Oscillation (ENSO) in the Pacific (Zebiak 1993).

Another factor is the signals from outside climate fluctuations that propagate into the Atlantic sector through atmospheric or oceanic tele-connection. Observations have shown that a part of the SST fluctuations in the tropical Atlantic is associated with the ENSO cycle in the tropical Pacific Ocean. There are also evidences of a connection between the tropical Atlantic variability and the North Atlantic Oscillation (NAO).

In this paper, we study the relative roles played by the remote ENSO effect and the air-sea coupling within the Atlantic Ocean in producing the observed tropical Atlantic SST variability. For this purpose, a regional coupling strategy is designed for a coupled ocean-atmosphere general circulation model (CGCM). Through a set of sensitivity experiments following this approach, we are able to isolate the regional air-sea interactions within the Atlantic sector from the remote ENSO forcing and to examine each of them closely.

In the next section, the CGCM, the coupling strategy, and the experiments will be described in more details. Then the results of this study will be discussed in Section 3.

2. EXPERIMENT DESIGN

The atmospheric component of the regional CGCM is the COLA atmospheric GCM (DeWitt and Schneider 1999). It is a global spectral model that is horizontally truncated at triangular wave number 42. Vertically it is divided into 18 unevenly spaced sigma levels. The model includes a state-of-the-art land surface model and physical parameterization of radiation, convection, and turbulence. The ocean component is the Poseidon quasi-isopycnal model (Schopf and Loughe 1995). It includes the world ocean between 70^{o}S-65^{o}N. The model has 14 vertical layers and a horizontal resolution of 0.5^{o}latitude x1.25^{o}longitude within 10^{o}S-10^{o}N. Later on, these two component models are referred to as AGCM and OGCM respectively.

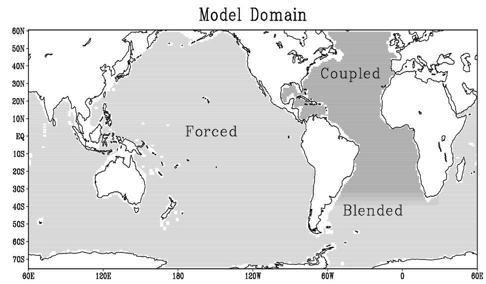

Figure 1 A schematic presentation of the RCGCM coupling strategy. The fully coupled region is darkly shaded. The prescribed region for both the oceanic and the atmospheric GCMs is lightly shaded. A blending zone is in between.

Figure 1 gives the coupled and the uncoupled regions within the OGCM domain, following the regional coupling strategy. The atmospheric and the oceanic components are fully coupled within the Atlantic Ocean 30^{o}S-65^{o}N (the darkly shaded area). The fluxes of heat, fresh water, and momentum at the sea surface as simulated by the AGCM are provided to the OGCM at daily intervals. The OGCM simulated SST for the same interval is then supplied to the AGCM. Outside this

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region, however, the two components are uncoupled (the lightly shaded area). In this region, SST data are prescribed at its sea grid points for the AGCM while the surface wind stress are prescribed at the air-sea interface for the OGCM. The surface heat and freshwater fluxes into the OGCM, however, are still from the AGCM, though with an addition of relaxation terms to the prescribed SST and the observed climatological monthly sea surface salinity data. A transition zone between the fully coupled and uncoupled regions is in the South Atlantic Ocean between 30^oS-40^oS, where the coupled model produced SST and surface fluxes are blended with the prescribed ones.

Two experiments have been conducted using this regional CGCM (RCGCM). In one case, climatological monthly surface wind stress and SST have been prescribed to drive both the atmosphere and the ocean in the uncoupled region (referred to as **CF** run). In the other case, however, real-time (monthly) SST data from U.S. Climate Prediction Center (CPC, Smith et al., 1996) and surface stress observations from the National Centers for Environmental Prediction (NCEP) reanalysis (Kalney et al., 1996) for the period of 1950-1998 are prescribed there(referred to as **RF** run).

In the **CF** run, there is no remote ENSO effect over the Atlantic sector. Its simulated interannual variability can only come from the regional air-sea interaction within the Atlantic sector and the forcing from the atmospheric internal variability. In the **RF** case, however, signals from the ENSO induced atmospheric tele-connection can be simulated as realistically as those from an uncoupled AGCM, while their interactions with the ocean in the Atlantic sector can be picked up through regional coupling. The remote ENSO effects should be more realistically simulated by this RCGCM run than a globally coupled GCM not only because the SST anomalies sensed by the AGCM have the right spatial-temporal structure and stronger amplitude but also because the atmospheric mean state is improved. It reduces the serious climate drift in the tropical Pacific sector common to present global CGCMs.

The ocean and atmosphere initial conditions for the **CF** run is separately derived from long-term uncoupled simulations of these two component models. The initial condition for the RF run was then derived from an instantaneous state of the **CF** run after ten years of coupled spin-up.

3. RESULTS

Both simulations produce qualitatively realistic mean fields of the SST, the surface wind stress, and the net surface heat flux in the fully coupled tropical Atlantic sector. Quantitatively, however, the simulated SST has a basin-wide cold bias with a maximum error of -2^oC. The simulated annual cycle near the sea surface is in phase with the observations in most of the region. In particular, the seasonal expansion of the equatorial cold tongue associated with the strengthening easterlies over the western Atlantic is well simulated. The amplitude of the model SST annual cycle, however, is slightly larger than the observed one. Another problem is the phase shift of the simulated annual cycle within the Caribbean Sea from the observations.

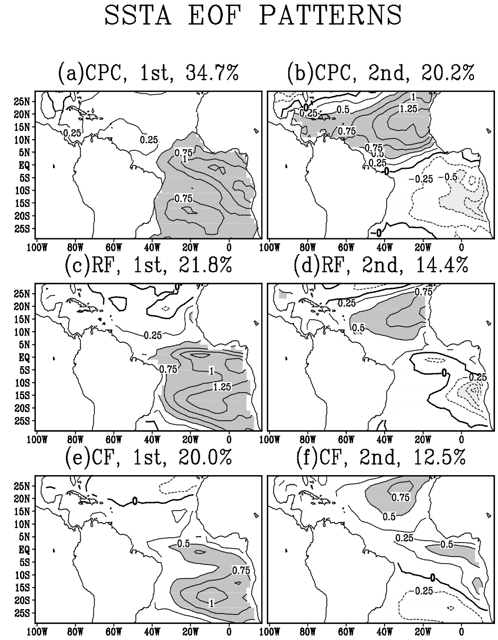

Figure 2 Spatial structures of the leading EOF modes of the SST anomalies from CPC analysis for 1950-1998 (a,b), **RF** run for 1950-1998 (c,d), and **CF** run for a 41-year simulation (e.f). The contour interval is 0.25^oC.

Figure 2 shows the spatial patterns of the two leading empirical orthogonal function (EOF) modes of the SST anomalies in the tropical Atlantic Ocean from the CPC analysis as well as the **RF** and **CF** runs. The 1^{st} EOF mode of the CPC data (Fig.2a) shows an basin-wide SST fluctuation with largest amplitudes extending from the southeastern to the equatorial ocean. There is also a secondary peak in the central part of the southern tropical Atlantic. The basic spatial structure of this mode has been reproduced by corresponding modes of both the **RF** (Fig.2c) and **CF** (Fig.2e) runs. The simulated modes generally show a somewhat stronger southern subtropical branch.

On the other hand, the 2^{nd} EOF mode of the CPC data (fig.2b) shows the SST dipole structure as mentioned before. Here opposite SST anomalies reside in the southern and the northern hemispheres, straddling the climatological position of the ITCZ. The centers of the two opposite poles are at the northeastern and southeastern coasts in the subtropical ocean. Major features of this pattern has been reproduced by the **RF** run, including the position of the major centers and the meridional asymmetry across the equator (Fig.2d), though its amplitude is weaker. The 2^{nd} EOF mode of the **CF** run, however, shows quite different spatial structure (Fig.2f). In this mode, there is no meridional asymmetry across the equator. In fact, SST fluctuations in the equatorial and southeastern ocean are in phase with variations in the subtropical North Atlantic.

A rotated EOF analysis, which depicts locally dominant signals, further demonstrates that major

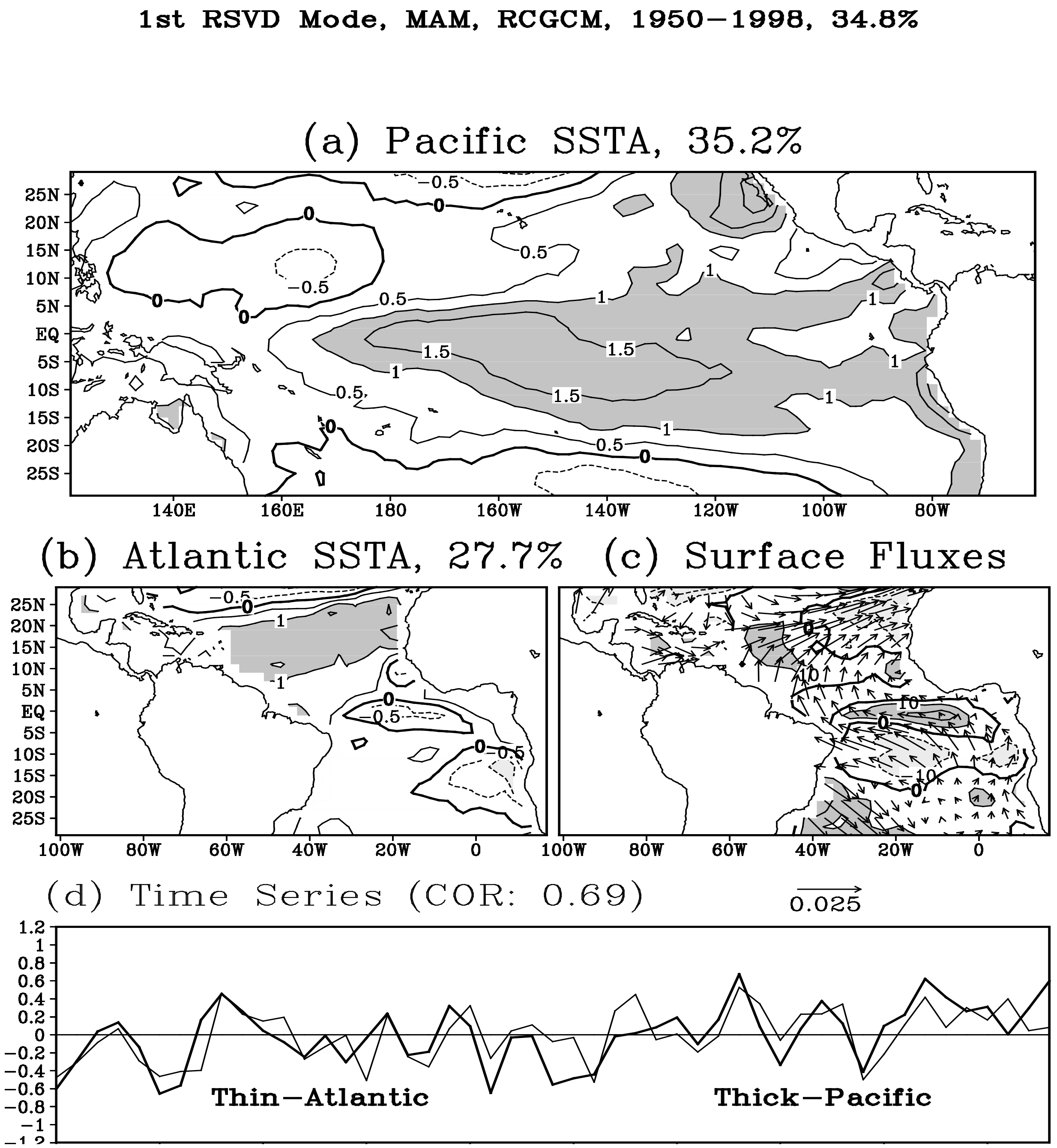

Figure 3 1st rotated SVD mode between March-April-May mean SST anomalies from observations in the Pacific Ocean (a) and RF run in the Atlantic (b). Their corresponding time series are in (d). Panel (c) shows the patterns of regression of the RF surface wind stress and heat flux anomalies to the Atlantic time series. The unit for the stress is N m^{-2}. The heat flux contour interval is 10 W m^{-2}. The number at the title is the covariance fraction explained by this mode, as defined by Cheng and Dunkerton (1995), which is a more realistic measure of the mode's weight than the more frequently used SCF (squared covariance fraction). The numbers on panel (a) and (b) are the percentages of variances accounted for by this mode for SSTA in each basin.

observational SST patterns in the equatorial and southern oceans are reproducible in both the **CF** and the **RF** runs. It suggests that these modes are part of an intrinsic variability sustainable through interactions between the ocean and the atmosphere within the Atlantic sector, or forced by the atmospheric interval variability. On the other hand, while the anomalous SST centered at the northern ocean is one of the leading modes for both the CPC data and the **RF** run, it is not significantly shown in the **CF** run. It implies that these northern SST signals are forced by remote factors.

This result is consistent with the different spatial distributions of the anomalous SST variance of the two simulations. The basin-averaged total variance of the SST anomalies within the tropical Atlantic between 30^oS-30^oN from the **RF** run is about 86% while the **CF** run accounts for 65% of the observed value. Though the magnitude of the SST anomalies in the **CF** run is generally weaker, the largest decrease is in the northern ocean.

Our further examination shows that the remote forcing to the northern tropical Atlantic Ocean is mainly associated with the SST anomalies in the tropical Pacific Ocean related to ENSO. Figure 2 presents the patterns and time series of the co-variation between the observed Pacific and **RF** simulated Atlantic SST anomalies in boreal spring for 1950-1998, based on its 1st rotated singular value decomposition (SVD) mode (Cheng and Dunkerton 1995). The corresponding patterns of the simulated anomalous surface wind stress and heat flux is shown in Fig.3c, which are derived by regression to the time series of the tropical Atlantic mode (Fig.3d, thin line).

This mode demonstrates that, during the boreal spring season while a Pacific El Niño event is in its maturing stage (Fig.3a), the northern tropical Atlantic Ocean becomes anomalously warm (Fig.3b). In fact, the El Niño induced atmospheric perturbations in the Atlantic sector cause stronger cross-equatorial flow and weaker northeast trades (Fig.3c), which in turn generate the oceanic change. This spatial structure in the tropical Atlantic region is very similar to a mode derived using the CPC and NCEP analyses for the same period (not shown). It is consistent to the recent study by Saravanan and Chang (2000), forcing an atmospheric GCM with prescribed SST anomalies in different ocean domains and examining the atmospheric responses over the tropical Atlantic.

This ENSO effect is strongest in boreal spring in observations, though the **RF** run also show substantial reduction of the northeast trades during the boreal winter in an El Niño year. Moreover, the ENSO induced SST anomalies persist into the boreal summer season in the northern tropical Atlantic Ocean in observations, as demonstrated by the pattern of regression coefficients to the NINO3 index one-season earlier. This effect, though existing, is somewhat weaker in the **RF** run.

4. ACKNOWLEGMENTS

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