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Coupled Ocean-Atmosphere Variability in the Tropical Atlantic Ocean

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A rotated empirical orthogonal function (REOF) analysis of the observed seasonal mean sea surface temperature (SST) anomalies for 1950-1998 from the tropical Atlantic basin shows that there are three important patterns of variability (Fig. 1):

1. Southern Tropical Atlantic (STA) Pattern (Fig.1a): The SST fluctuations are centred near the Angola coast and expand toward the equator into the Gulf of Guinea.

2. Northern Tropical Atlantic (NTA) Pattern (Fig.1b): This pattern is characterized by SST anomalies centred near the African coast in the northern tropical Atlantic Ocean.

3. Southern Subtropical Atlantic (SSA) Pattern (Fig.1c): The SST fluctuations are in the open ocean of the subtropical South Atlantic.

Both the STA and NTA have been shown as leading tropical Atlantic modes in many previous studies (see, e.g., Enfield and Mayer, 1997; Dommenget and Latif, 2000), which contribute to the fluctuation of the equatorial SST meridional gradient. The SST gradient then affects the position of the inter-tropical convergence zone (ITCZ) and rainfall over the ocean and its adjacent regions (Nobre and Shukla, 1996). The STA is also associated with the anomalous events in the Gulf of Guinea and near the Angola coast (Hirst and Hastenrath, 1983; Huang et al., 1995). The SSA has been demonstrated to be the dominant SST fluctuation in the subtropical South Atlantic Ocean (Venegas et al., 1997). Previous studies also demonstrated that regional air-sea coupling (e.g., Zebiak, 1993; Chang et al., 1997) and remote forcing factors, such as the El Niño/Southern Oscillation (ENSO), play roles in forming some of these SST patterns (e.g., Nobre and Shukla, 1996; Enfield and Mayer, 1997; Saravanan and Chang, 2000; Czaja et al., 2002). The scientific question, then, is whether these SST patterns are externally forced or can be generated as intrinsic modes of the tropical Atlantic ocean-atmosphere processes.

To answer these questions, we have analysed the Atlantic Ocean variability simulated by a coupled ocean-atmosphere model, in which ocean-atmosphere coupling is included only within the Atlantic Ocean between 30°S-65°N. Therefore, one major potential remote-forcing factor to the tropical Atlantic, the ENSO, is suppressed. The oceanic and atmospheric components of the coupled GCM, referred to as the OGCM and the AGCM respectively hereafter, are described in more detail by Huang et al. (2002). In the coupled region, all surface fluxes simulated by the AGCM and the SST simulated by the OGCM are supplied, each to the other component, at daily intervals. Over the uncoupled portion of the global domain, the SST is prescribed for the AGCM and the surface wind stress is prescribed for the OGCM with observed monthly climatological data. A 10°-wide zone in the South Atlantic Ocean within 30°S-40°S is used to blend the coupled and uncoupled portions of the domain. The coupled run has been conducted for 200 years. The output from the last 110 years is used in this analysis.

Our results show that the leading SST patterns shown in Fig. 1 can be reproduced quite realistically by this regionally coupled model (Fig. 2). In particular, the model NTA and SSA patterns (Fig. 2b, c) have amplitudes comparable to their observed counterparts (Fig. 1b, c) and explain a significant amount of the total variance. This seems to suggest that these patterns can be produced by air-sea coupling within the Atlantic Ocean or by the oceanic responses to atmospheric internal forcing, in which there was no external SST forcing.

The model STA pattern (Fig. 2a), however, is weaker in its strength, especially to the north of 10°S, and explains much less variance, than it does in the observations (Fig. 1a). Since the observed STA pattern implies air-sea interactions sensitive to the equatorial wind in the western and central Atlantic (Hirst and Hastenrath, 1983; Zebiak, 1993), its weak amplitude in the coupled model suggests that these equatorial processes are not adequately simulated. We suspect that this situation is related to a warm mean SST bias to the south of the equa-

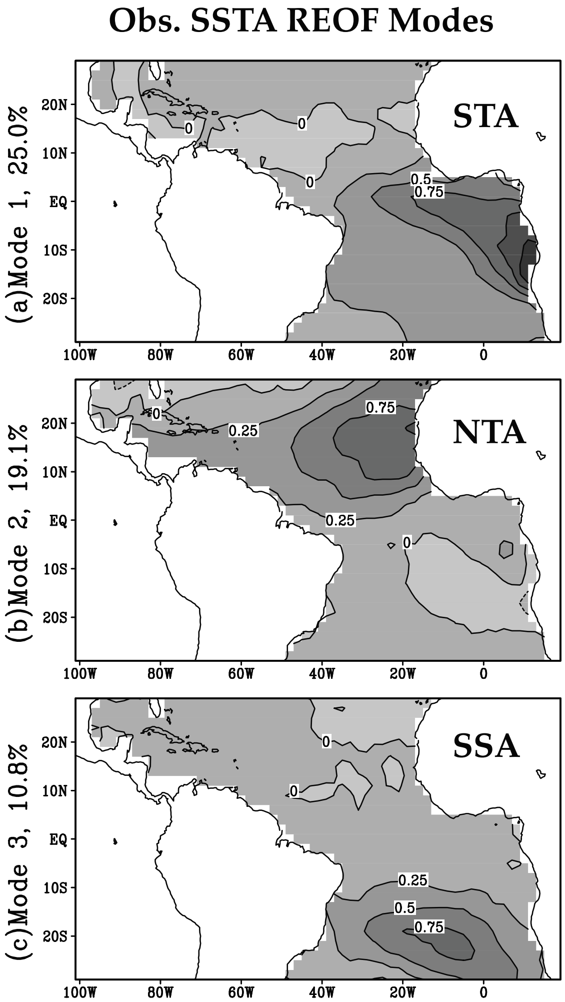

Fig. 1: The spatial patterns of the (a) 1st, (b) 2nd, and (c) 3rd REOF modes of the seasonal mean SST anomalies for 1950-1998. The SST data are from U.S. Climate Prediction Center's analysis. The magnitude of the patterns corresponds to two times of the standard deviation of the normalized time series. The contour interval is 0.25°C.

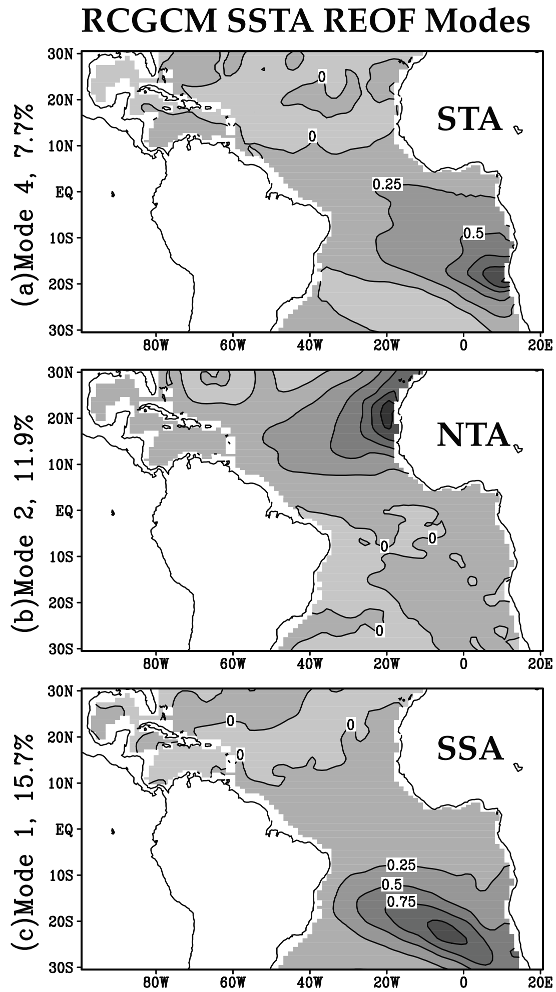

Fig. 2: The spatial patterns of the (a) 4th, (b) 2nd, and (c) 1st REOF modes of the seasonal mean SST anomalies from the 110-year regional coupled GCM simulation. The magnitude of the patterns corresponds to two times of the standard deviation of the normalized time series. The contour interval is 0.25°C.

tor. The bias then is related to the fact that in the coupled model the ITCZ has two preferred locations. From boreal summer to fall, the ITCZ is located to the north of the equator. However, it shifts to the south of the equator from January to May. During these months, it tends to block the southeast trade winds from reaching the equatorial zone.

The effect of this systematic error on the SST variability can be seen in the structure of the standard deviation of SST anomalies in the model (Fig. 3b). Although the model reproduced the main features of the observed variability (Fig. 3a), its major difference from the observations is a zonal belt of minimum standard deviation (less than 0.3°C) between 5°-15°S. This zone largely cuts off the link between the fluctuations near the Angola coast and those within the equatorial wave-guide and splits them into two separate modes. In reality, however, they are closely connected (Fig. 3a, see also, Hirst and Hastenrath, 1983). As a result, the model STA pattern is significantly weakened. Our composite analysis based on time series of the STA modes shows that, unlike the observations, the model STA pattern is much less correlated with the equatorial winds in the central and western equatorial Atlantic.

Our further analysis suggests that anomalous events associated with both the NTA and the SSA are mainly associated with the anomalous surface heat fluxes caused by the changing trade winds. The wind changes, in turn, are associated with the fluctuations of the subtropical anticyclones in the atmosphere, which, apart from regional air-sea interactions within the tropical Atlantic, are also connected with the extra-tropical varia-

Standard Deviation, SSTA (ºC)

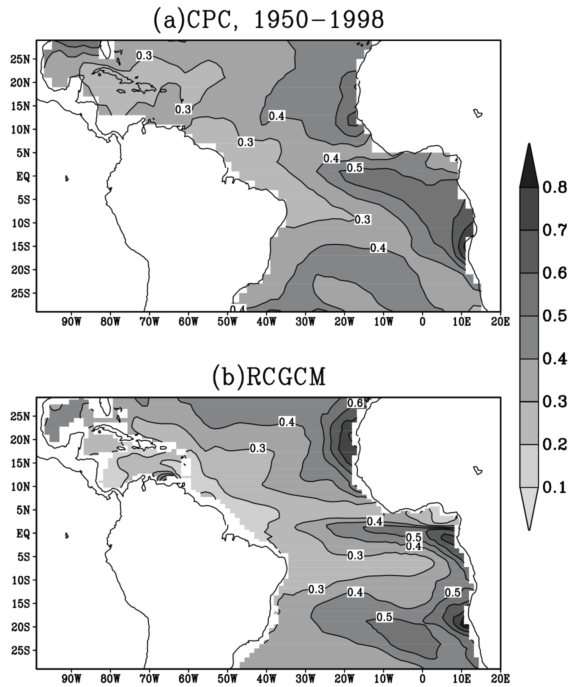

Fig. 3: The spatial structure of the standard deviation of the seasonal mean SST anomalies from (a) U.S. Climate Prediction Center's Analysis for 1950-1998 and (b) 110-year simulation of the regional coupled GCM. The contour interval is 0.1ºC. The SST anomalies are seasonally averaged data.

tions. For NTA, they seem to be related to the North Atlantic Oscillation while low-frequency Rossby waves (Hoskins and Karoly, 1981) propagating from the west may also play a role. For SSA, there is a significant connection to the Antarctic Oscillation (Gong and Wang, 1999). Since climatological SST is prescribed outside the Atlantic domain and in the global southern extra-tropical oceans, some anomalous atmospheric signals from the global atmospheric internal variability (Straus and Shukla, 2002) might propagate into the coupled Atlantic domain. However, the local coupled processes may further modify these signals. For instance, after the SST anomalies are initiated by these forcings, regional air-sea processes seem to expand these anomalies further toward the equator on a seasonal time scale.

In a previous study using the regional coupled model forced with observed SST in 1950-1998 over the uncoupled domain, Huang et al. (2002) found significant ENSO influences on the NTA, which is similar to the observed ENSO-NTA relationship (Enfield and Mayer, 1997). The present experiment suggests that the spatial pattern of NTA is mainly determined by ocean-atmosphere coupling within the Atlantic Ocean. The main effect of ENSO may be primarily to modulate the temporal evolution of the NTA through influencing atmospheric planetary waves propagating into the basin.

These results on NTA and SSA are largely consistent with those derived by Dommenget and Latif (2000) based on annual mean SST data from several globally coupled ocean-atmosphere general circulation models (CGCM). In fact, the two leading REOF modes of our model simulation, the SSA (Fig. 2c) and NTA (Fig. 2b), are very similar to the two leading modes from the models Dommenget and Latif (2000) have shown. However, our interpretation and explanation of the patterns in the southern ocean are different. In model simulations reported by Dommenget and Latif (2000), a pattern similar to the observed SSA is found as a leading mode for all the models. They further noticed that this model mode is strongly affected by subtropical atmospheric fluctuations. However, Dommenget and Latif (2000) have interpreted that mode to be a simulation of the observed STA and concluded that STA is mainly caused by forcings from the subtropics. Therefore, they suggested that the main patterns in both hemispheres resemble local oceanic responses to atmospheric fluctuations from the subtropics, with air-sea feedback and ocean dynamics having little effect in the tropics. Our conclusion in this respect is different from Dommenget and Latif (2000). Based on our results, the contribution of the regional air-sea coupling and oceanic dynamics may still be significant, especially for STA, even though it is underestimated due to the systematic errors of the present coupled ocean-atmosphere general circulation models.

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Interior Ocean Pycnocline Transports in the Atlantic Subtropical Cells

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1. Introduction

Subtropical Cells (STCs) are shallow meridional overturning cells that transport water subducted in the subtropics during the winter season to the tropics, where it is upwelled to the surface. The upwelled water is modified by air-sea heat exchange and then advected back to the subtropics by poleward Ekman flows in the surface layer to complete the STC. The STCs in the Pacific have been extensively studied both observationally and theoretically (e.g., McCreary and Lu, 1994; Liu et al., 1994; and Johnson and McPhaden, 1999), and several recent studies suggest STCs may play a role in regulating the low frequency climate variability involving tropical Pacific SST (Gu and Philander, 1997; Kleeman et al., 1999; McPhaden and Zhang, 2002). Unlike the STCs in the Pacific, fewer studies have been conducted on the STCs in the Atlantic, though several modelling papers (Fratantoni et al., 2000; Inui et al., 2002; Lazar et al.,. 2002; Malanotte-Rizzoli et al., 2000; Harper, 2000; Jochum and Malanotte-Rizzoli, 2001) have recently appeared. These studies suggested strong dependence of the strength and mean pathways of STCs on model configurations and climatological forcings. Differences between the model simulations may also be attributed to differences in how the large scale Thermohaline Circulation (THC) is simulated in the models. Here we form a high resolution hydrographic climatology for the Atlantic to describe the subsurface limb of STCs, which connect the tropical-extratropical Atlantic in the pycnocline. The primary data set is a combination of the World Ocean Database (Conkright et al., 1999) from the National Oceanographic Data Center (NODC), new hydrographic data collected during the World Ocean Circulation Experiment (WOCE), and data collected during cruises to service Pilot Research Moored Array in the Tropical Atlantic (PIRATA) moorings. A total of 86,131 casts with both temperature and salinity measurements in the Atlantic between 40^{o}S and 50^{o}N reach a depth of at least 1200 m, which is the reference level we use for our geostrophic velocity estimates. The number of casts available for defining water mass properties at shallower levels is considerably greater (e.g. 166,941 casts reach at least 300 m). By decade, the number of available cast ranges between about 7,000 - 30,000 to 1200 m and 13,000 - 53,000 to 300 m, with maximum sampling taking place in the 1970's and 80's.

2. Flow on Isopycnal Surfaces in the Pycnocline

Flow in the Atlantic STCs is concentrated on isopycnal surfaces that outcrop and are ventilated in the subtropics. Temperature, salinity, geostrophic streamlines, and potential vorticity (N^2f/g, where N is the buoyancy frequency, f is Coriolis parameter, and g is gravitational acceleration) are calculated on these isopycnal surfaces and averaged from 1950-2000. Calculations are performed using the Hydrobase analysis package (Curry, 1996), which implements isopycnal averaging to grid individual profiles along their density surfaces into bins on a 0.25^o latitude x 0.25^o longitude grid. The resulting bin-averaged profiles are then mapped onto 0.5^o x 0.5^o grid using objective analysis with zonal and meridional de-correlation scales set at 5^o longitude x 2^o latitude. To illustrate the basic structure of STCs, we show the fields of planetary potential vorticity (PV) and salinity on the 25.4 σ_θ isopycnal surface (roughly equivalent to 20^{o}C) in the upper pycnocline (Fig. 1a, b, page 37). The PV field is characterized by the high PV ridge extending from the eastern boundary near 15^{o}N to the western part of the basin near 10^{o}N, almost reaching the western boundary. This PV ridge underlies the Inter-tropical Convergence Zone (ITCZ) where wind stress curl pumps the pycnocline up toward the surface and vertically compresses density surfaces. Also shown are the wintertime outcrop lines of this surface in both the Northern and Southern Hemisphere. Assuming that PV is approximately conserved along trajectories, water subducted in the Northern Hemisphere subtropics on this density surface would have to take a convoluted pathway around the western rim of this PV ridge to get to the equatorial region (McCreary and Lu, 1994). In contrast, the PV field in the Southern Hemisphere is more uniform, allowing for a more direct interior pathway between the subtrop-