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Coupled Aspect of Atlantic Ocean-Atmosphere Variability

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Abstract. This report is based on an overview talk given at the CLIVAR workshop on "Shallow tropical/subtropical overturning cells and their interactions with the atmosphere" that took place in Venice, Italy, October 9-13, 2000. After briefly touching upon observational studies, this report reviews the recent progress in coupled modeling of tropical Atlantic variability (TAV). This is followed by a discussion on the challenge we face in consolidating some mutually conflicting results from AGCM and CGCM simulations and in assessing the role of ocean dynamics in Atlantic climate variability.

1. Empirical studies

The tropical Atlantic and Pacific share many common climatological features, such as a cold tongue and eastward shoaling of the thermocline on the equator, prevailing easterly trade winds, and a northward displaced ITCZ (Fig. 1). Given that the solar radiation is both zonally uniform and symmetric about the equator, the establishment of these climatological features involves ocean-atmosphere-land interaction.

Because of the east-west asymmetry in the climatology, the Atlantic also sees an equatorial mode of SST variability much like the Pacific ENSO. This Atlantic Nino mode is captured by a rotated EOF analysis by Ruiz-Barradas et al. (2000). When an Atlantic warm event occurs, atmospheric deep convective heating increases near the equator, inducing anomalous westerlies in the western equatorial Atlantic (Fig. 2). In response to this change in zonal wind, the thermocline deepens in the east, helping sustaining/amplifying the SST warming. This is exactly the same Bjerknes feedback that gives rise to the ENSO in the Pacific. But because of the small zonal size of the Atlantic Ocean, this equatorial coupled mode is likely to be damped, excited by stochastic forcing (Zebiak 1993).

How to characterize the rest of tropical Atlantic SST variability is under much debate and a subject of active research. Based on EOF analysis, one school of thought contends that there is a dipole mode that is anti-symmetric about the annual-mean ITCZ (Servain 1991; Nobre and Shukla 1996; Fig. 3). This SST pattern is known to be associated with rainfall variability in the Northeast Brazil and Sahel. The other school of thought argues that the dipole mode is unphysical and an artifact of EOF analysis (Houghton and Tourre 1992; Enfield and Mayers 1997; Mehta 1998) by pointing out the fact that the SST anomalies are organized on one side of the equator, and do not significantly correlated across the equator (Fig. 4). Some studies show the interhemispheric SST correlation may change sign according to time scales; SST anomalies tend to be negatively (positively) correlated between the tropical North and South Atlantic on the decadal (interannual) time scale (Tanimoto and Xie 1999; Enfield et al. 1999). But a study by Mehta (1998) finds no interhemispheric coherence at any frequency band.

Results from empirical studies agree that there are two or more modes of SST variability in the tropical Atlantic, but they disagree on what these modes are. The lack of interhemispheric correlation can be interpreted as the evidence for independent tropical North and South Atlantic modes. Equally plausible is the argument that a monopole and dipole, of equal amplitudes, interfere with each other, causing an apparent lack of correlation across the equator. Given the limited length of observation record, it is difficult to draw firm conclusions as to which decomposition, northern and southern modes vs. monopole and dipole modes, is physical. Such a determination may be further complicated by the possibility that the spectra of these modes are red and do not have distinct peaks.

2. Coupled modeling

On the modeling front, much progress has been made in understanding the cause of off-equatorial SST variability and the roles of ocean-atmosphere interaction. Carton et al. (1996) carry out a set of OGCM experiments by modifying the atmospheric forcing through wind stress and wind-induced evaporation. While equatorial variability is largely due to wind stress-forced thermocline variations, off-equatorial SST variability, particularly that in the interhemispheric SST gradient, is caused mainly by wind-induced evaporation (Fig. 5).

Chang et al. (1997) suggest that the variability of interhemispheric SST gradient involves air-sea interaction and invoke a wind-evaporation-SST (WES) feedback to explain Carton et al.'s OGCM results in a coupled context. A dipole pattern of SST anomalies like the one in Fig. 2 induces southerly cross-equatorial winds, which acquire an easterly (westerly) component because of the Coriolis force in the Southern (Northern) Hemisphere. These anomalous winds enhance (weaken) the background trade winds and hence the evaporative cooling south (north) of the equator, and these wind-induced changes in evaporation act to amplify the initial SST anomalies. Chang et al. further couple an empirical atmosphere model with two separate ocean models and show that the dipole mode is dominant in these coupled models if the thermodynamic feedback is strong enough (Fig. 6). They suggest that the advection by the cross-equatorial North Brazil Current is responsible for the phase change and sets the decadal time scale for the dipole oscillation in their models.

An alternative phase-changing mechanism is proposed by Xie (1999). In addition to an in-phase relation between wind and SST anomalies that gives rise to the positive WES feedback, the maximum westerly wind anomaly is located equatorward of the maximum SST anomaly, an effect of the geostrophy. This meridional phase shift creates a tendency for the coupled anomalies to propagate toward the equator (Fig. 7b). This tendency of equatorward propagation is slowed down by the mean poleward Ekman advection (Fig. 7a) under the prevailing easterly trade winds.

The small amplitudes of tropical Atlantic variability (SST rms ~ 0.4 C) suggest that all coupled modes may be damped and thus need to be excited by external forcing. In response to mutually uncorrelated random forcing in the subtropical North and South Atlantic poleward of 25^o latitude, SSTs in a coupled WES model varies at slow time scales in an anti-symmetric mode (Fig. 8; Xie and Tanimoto 1998). When the dipole mode is only weakly damped, the spectrum of the cross-equatorial SST gradient shows a peak at its intrinsic frequency. In the presence of strong damping, however, the spectrum becomes red. Even in this strongly damped case, the coupled dipole, as the least damped mode of the system, still leaves strong marks in the time-space structure of model variability. First, the spectral power starts to level off around the intrinsic frequency of the free dipole mode. Second, the coupled mode gives rise to the characteristic dipole structure even if the northern and southern forcing is mutually uncorrelated.

In a general sense, there are two modes of ocean-atmosphere interaction in the tropical oceans. Within the equatorial upwelling zone where the coupling between the thermocline depth and SST is strong, the Bjerknes feedback involving zonal interaction of equatorial wind, thermocline depth and SST dominates, giving rise to ENSO in the Pacific and Atlantic. Off the equator, on the other hand, the general downwelling renders the ocean dynamics ineffective in changing SST, leaving surface heat flux to play an important role in SST variability. In a large ocean basin like the Pacific, the ENSO mode that is strongly trapped on the equator dominates. The Bjerknes feedback weakens in a small domain like the Atlantic (Zebiak 1993), allowing a weak WES dipole mode to become the leading mode (Fig. 9; Xie et al. 1999). In the particular calculation shown in Fig. 9, the equatorial Bjerknes mode has a slightly smaller than but comparable growth rate with the dipole mode, suggesting that they may coexist.

3. Atmospheric response

In the simple and intermediate coupled models, the existence of a dipole mode can be confirmed by suppressing ocean dynamic effects and hence the Bjerknes feedback. In fully coupled GCMs, such sensitivity experiments are much more difficult to carry out if not impossible. The lack of interhemispheric SST correlation in some coupled GCMs has led to a speculation that the observed wind anomaly pattern in Fig. 3 may act as a one-way forcing to the ocean, but is not a response to the SST dipole (Dommenget and Latif 2000). If true, the dipole is merely a passive response to some fortuitous arrangement of winds.

Attempts to determine the atmospheric response to a prescribed SST dipole with atmospheric GCMs have yielded mixed results. Dommenget and Latif (2000) claim that the ECHAM3 does not show significant response to a SST dipole. Sutton et al. (2000) obtain similar results in the HadAM1 while noting a significant response in the ITCZ and cross-equatorial wind. Chang et al. (2000) report significant response in both meridional and zonal wind components within a latitudinal band between 10S and 10N in the CCM3. The apparent disagreement among the GCMs (Fig. 10) can arise from differences in model physics, but may also be partially due to the difficulty in obtaining stable statistics in the presence of strong internal chaotic variability of the atmosphere.

Okumura et al. (2000) prescribe a dipole pattern of SST anomalies (SSTAs) in the tropical Atlantic that does not change with time, and carry out long integrations of an atmospheric GCM until stable statistics of model anomaly fields are obtained. They find that the Atlantic ITCZ shifts into the warmer hemisphere, with the trade winds relaxing (intensifying) on a tropical-wide scale over the warm (cold) SSTAs, much as in observations and in support of the WES feedback (Fig. 11a).

The existence of this WES feedback is further confirmed by results from a coupled model with the same AGCM as its component. A clear north-south seesaw due to the WES feedback is clearly visible in a latitude-time section of SSTAs (Fig. 12; Xie and Saito 2000). The dominance of the dipole mode in this coupled model is partially due to the suppression of the thermocline feedback in the intermediate ocean model.

The atmospheric response to a tropical SST dipole is not limited to the tropics, but also include a barotropic component that extends into the extratropics. When coupled with an interactive ocean mixed layer of 50 m deep, the AGCM response closely resembles a composite of observational data based on an index of cross-equatorial SST gradient (Fig. 11), both having a projection onto the NAO. In response to a negative tropical SST dipole, the Azores high centered at 40N strengthens, and so does the Icelandic low albeit with a smaller amplitude. The winter cold surges in the eastern US and Canada weaken substantially. A pair of SSTA centers appear off the US and Canadian coast, respectively, associated with changes in the speed of prevailing westerlies and forming the extratropical portion of the North Atlantic tripole.

Astride the trade and westerly wind regimes, the Azores high appears to be an important bridge between the tropical and extratropical North Atlantic. Okumura et al.'s results indicate that the tropical SSTAs can affect the extratropical North Atlantic through atmospheric teleconnection. Watanabe and Kimoto (1999) and Robertson et al. (2000) obtain similar results, albeit each based on one single integration forced by global observed SSTs. This Azores bridge appears not to be a one-way process, and can act the other way around. When forced by observed wind poleward of 20^{o} latitude, a coupled WES model can reproduce the observed time series of interhemispheric differences in SST and zonal wind (Fig. 13). Thus, the extratropical and tropical Atlantic may be fully interactive through the Azores variability.

It is even less clear whether the extratropical North Atlantic supports coupled ocean-atmosphere modes. The NAO appears to show a significant response to the North Atlantic SST tripole (Rodwell et al. 1999; Mehta et al. 2000), and may thus provide a weak feedback onto the SSTAs. On the other hand, other studies suggest that the tripole pattern is mainly determined by the dominant atmospheric stationary eddy arrangement or NAO, and results from the passive ocean response to stochastic forcing by the NAO (Delworth and Mehta 1998; Seager et al. 2000). On the other hand, the ocean gyre adjustment (Grotzner et al. 1998; Marshall and Czaja 2000), advection by the North Atlantic Current

(Sutton and Allan 1997), and thermohaline circulation (Delworth et al. 1993) have also been implicated as important in generating low-frequency North Atlantic SST variability.

4. Implications for STC studies

The study of the Atlantic STCs is just beginning and its role in the climate and its variability needs to be determined. A recent simulation of the Atlantic circulation indicates that the bifurcation latitudes of the western boundary currents are 12N and 15S, respectively (Inui et al. 2000; Fig. 14). Changes in trade winds associated with off-equatorial modes of SST variability (e.g., Fig. 3) can affect the strength of the STCs and thus the transport of the cold thermocline water into the tropics. Kleeman et al. (1999) suggest that this $v'\overline{T}$ mechanism leads to decadal ENSO modulation in the Pacific.

The $\overline{v}T'$ mechanism of Gu and Philander (1997) may also operate in the Atlantic where SST variability in the subtropics is as strong as on the equator. Lazar et al. (2000) show that the subducted thermal anomalies are strongly dissipated in the western boundary region before reaching the equator much as in the Pacific (Schneider et al. 1999; Nonaka and Xie 2000).

There are a number of noteworthy differences in the STCs between the Pacific and Atlantic. First, the northernmost latitude where the subducted water feeds into the equatorial Atlantic is much more southward than in the North Pacific because of the meridional overturning cell. This determines that the subducted thermal anomalies that can affect the equatorial SSTs through the Gu and Philander mechanism must be of tropical origin in the Atlantic. Second, whereas the tropical dipole mode appears ideal to supply SSTAs for subduction and force the STC strength change through its wind variability, it is anti-symmetric about the ITCZ. Thus, STC-related anomalies from the two hemispheres may cancel each other when they reach the equator. However, the Atlantic climatology in general and its ITCZ in particular are not symmetric about the equator, leaving room for the STCs to play a role, but this role appears to be more complicated than in the Pacific.

5. Summary

a. There is an equatorial ENSO-like mode in the Atlantic due to the Bjerknes feedback.
b. Empirical analysis of observational data does not yet give conclusive answers as to how to characterize the tropical Atlantic SST variability.
c. Some coupled models suggest that the cross-equatorial SST gradient is controlled by a coupled mode of ocean-atmosphere interaction that is anti-symmetric about the equator.
d. Atmospheric response to a prescribed SST dipole disagrees among AGCMs, although they agree on the response to ENSO-like equatorial SST anomalies. This disagreement calls for a better understanding of atmospheric response to SST anomalies over cold ocean surface, where the planetary boundary layer processes are likely important.
e. The Azores high can potentially act as a two-way bridge that allows the tropical and extratropical North Atlantic to interact.

f. The roles of ocean dynamics including the STCs' are poorly understood in the tropical Atlantic and need further investigations.

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