Interaction between Tropical Atlantic Variability and El Niño–Southern Oscillation

R. SARAVANAN
National Center for Atmospheric Research,* Boulder, Colorado

PING CHANG
Department of Oceanography, Texas A&M University, College Station, Texas

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ABSTRACT

The interaction between tropical Atlantic variability and El Niño–Southern Oscillation (ENSO) is investigated using three ensembles of atmospheric general circulation model integrations. The integrations are forced by specifying observed sea surface temperature (SST) variability over a forcing domain. The forcing domain is the global ocean for the first ensemble, limited to the tropical ocean for the second ensemble, and further limited to the tropical Atlantic region for the third ensemble. The ensemble integrations show that extratropical SST anomalies have little impact on tropical variability, but the effect of ENSO is pervasive in the Tropics. Consistent with previous studies, the most significant influence of ENSO is found during the boreal spring season and is associated with an anomalous Walker circulation. Two important aspects of ENSO’s influence on tropical Atlantic variability are noted. First, the ENSO signal contributes significantly to the “dipole” correlation structure between tropical Atlantic SST and rainfall in the Nordeste Brazil region. In the absence of the ENSO signal, the correlations are dominated by SST variability in the southern tropical Atlantic, resulting in less of a dipole structure. Second, the remote influence of ENSO also contributes to positive correlations between SST anomalies and downward surface heat flux in the tropical Atlantic during the boreal spring season. However, even when ENSO forcing is absent, the model integrations provide evidence for a positive surface heat flux feedback in the deep Tropics, which is analyzed in a companion study by Chang et al. The analysis of model simulations shows that interannual atmospheric variability in the tropical Pacific–Atlantic system is dominated by the interaction between two distinct sources of tropical heating: (i) an equatorial heat source in the eastern Pacific associated with ENSO and (ii) an off-equatorial heat source associated with SST anomalies near the Caribbean. Modeling this Caribbean heat source accurately could be very important for seasonal forecasting in the Central American–Caribbean region.

1. Introduction

The ENSO phenomenon is by far the dominant feature of interannual variability in the climate system (Philander 1990). Although it is primarily a tropical Pacific phenomenon, its effects are felt in many parts of the globe. The remote influence of ENSO occurs through atmospheric teleconnections, the best known of which is the Pacific–North American (PNA) pattern, which links ENSO to variability in the North Pacific and North American regions (Wallace and Gutzler 1981). This linkage is believed to be accomplished through barotropic Rossby wave propagation (Hoskins and Karoly 1981).

In addition to the strong extratropical connection, observational studies show that ENSO is also linked to variability in other tropical regions such as the Asian summer monsoon and the tropical Atlantic variability. The mechanisms responsible for these tropical linkages are, however, less well understood than those responsible for the extratropical linkages. In this study, we focus on the link between ENSO and tropical Atlantic variability. Although observational aspects of this linkage have been known for quite some time (e.g., Covey and Hastenrath 1978; Hastenrath et al. 1987; Curtis and Hastenrath 1995; Nobre and Shukla 1996; Enfield 1996; Enfield and Mayer 1997; Uvo et al. 1998; Klein et al. 1999; Giannini et al. 2000; Enfield and Mestas-Nuñez 1999), modeling studies have begun to address it only in recent years (e.g., Zebiak 1993; Latif and Barnett 1995; Harzallah et al. 1996).

Atmosphere–ocean interaction in the tropical Atlantic may not be as spectacular as in the adjacent tropical

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Corresponding author address: R. Saravanan, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000. E-mail: svn@ncar.ucar.edu

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Pacific region, but it does exhibit some very interesting features. Perhaps the most robust of these is the correlation between tropical Atlantic SST and rainfall over northern Nordeste (NNE) Brazil. This correlation is characterized by a dipole SST structure straddling the equator and has been the subject of numerous observational and modeling studies (Hastenrath and Heller 1977; Moura and Shukla 1981; Hastenrath 1984; Servain 1991; Mehta and Delworth 1995; Harzallah et al. 1996). This dipole correlation structure has long been interpreted as evidence for the existence of a strong “dipole mode” of variability in the tropical Atlantic.

Another feature of tropical Atlantic variability that has recently been the subject of discussion is the positive correlation between SST anomalies and downward surface heat flux. Chang et al. (1997) have noted that the dipole mode is characterized by downward surface heat flux over the positive SST anomaly and vice versa and have interpreted this relationship as a positive feedback that sustains the cross-equatorial SST gradient and cross-equatorial wind variability. The proposed mechanism for the positive feedback is based upon wind-induced changes in the latent heat flux (Carton et al. 1996; Chang et al. 1997).

In the midlatitudes, a positive correlation between SST and the downward surface heat flux is usually indicative of the forcing of the ocean by internal atmospheric variability (e.g., Saravanan 1998; Frankignoul 1999). In the Tropics, however, internal sources of quasi-stationary atmospheric variability are quite weak; much of the spatially coherent variability in the Tropics is in fact closely tied to SST variability. This suggests that the positive correlation between SST and downward surface heat flux may indeed be a signature of positive feedback in air–sea interaction.

Some recent observational and modeling studies have questioned the above scenario of tropical Atlantic variability, especially the existence of a dipole mode (Houghton and Toure 1992; Enfield and Mayer 1997; Mehta 1998; Enfield et al. 1999; Dommenget and Latif 2000). These studies highlight the fact that the observed correlation between SST anomalies north and south of the equator is not strong enough, as would be characteristic of a dipole, but actually close to zero. In this alternative scenario, the interhemispheric SST anomalies in the tropical Atlantic are essentially independent of each other and are governed by dynamical processes local to each hemisphere.

At this juncture, it is useful to clearly distinguish between a dipole mode, which requires the existence of anticorrelated variability between the two hemispheres, and the atmospheric response to the cross-equatorial SST gradient. The latter process can be important even in the absence of a dipole mode because uncorrelated monopolar variability in each hemisphere is also associated with cross-equatorial SST gradients (Enfield et al. 1999).

We argue that part of the reason for the controversy regarding the dipole mode relates to the difficulty in distinguishing between local and remote interactions in the tropical Atlantic. In particular, it is important to separate the remote effects associated with ENSO from the truly local air–sea interaction in the tropical Atlantic (Enfield et al. 1999).

Although the importance of the remote influence of ENSO is well recognized, there is as yet no clear consensus on the mechanisms by which ENSO actually affects tropical Atlantic variability. The recent observational studies by Curtis and Hastenrath (1995), Enfield and Mayer (1997), Klein et al. (1999), and Giannini et al. (2000) show that ENSO makes a significant contribution to SST variability in the tropical Atlantic. These studies find that significant ENSO-related warmings occur in the northern tropical Atlantic during the boreal spring season. Correlations between ENSO and SST in the equatorial Atlantic are quite weak, especially in the eastern part of the basin (Zebiak 1993). These results differ somewhat from those of Latif and Barnett (1995), who suggest that the dominant Atlantic response to ENSO is a cooling of SST in the equatorial Atlantic. Further, the modeling study of Harzallah et al. (1996) finds two distinct modes of variability that affect NNE Brazil precipitation, both related to the “Atlantic dipole” but only one related to ENSO. The predictability study of Penland and Matrosova (1998) finds that the remote influence of ENSO contributes to much of the seasonal predictability in the northern tropical Atlantic and also suggests that the ENSO influence disrupts the dynamics of the Atlantic dipole.

More than one mechanism has been proposed to explain the linkage between ENSO and tropical Atlantic variability. One way to explain this linkage is in terms of an anomalous Walker circulation (e.g., Kidson 1975). An alternative explanation is that this linkage is accomplished through tropical–extratropical interaction, namely through the PNA teleconnection pattern that originates in the tropical Pacific and propagates via the extratropics into the northwestern region of the tropical Atlantic (e.g., Nobre and Shukla 1996).

In this study, we use a suite of atmospheric general circulation model (AGCM) integrations forced by observed SST variability to achieve the separation between local and remote effects. The spatial domain over which the SST variability is allowed to force the atmosphere is progressively reduced from a global domain to a tropical domain and finally to a tropical Atlantic domain. This allows us to isolate the remote effects of ENSO on the tropical Atlantic, which will be the primary focus of this study.

Our study uses simple correlation–regression techniques using area-averaged SST indexes such as the Niño-3 SST index to distinguish between local and remote effects. Although the remote effects of ENSO are fairly well identified by this technique, the area-averaging approach misses out many of the finescale features of the near-surface local feedbacks. A companion study...
by Chang et al. (2000) uses a statistical signal-to-noise maximizing technique to provide a detailed analysis of the near-surface response to tropical Atlantic SST anomalies. Their study also provides an in-depth discussion of the role of internal atmospheric variability and the evidence for true positive air–sea feedbacks in the tropical Atlantic, a topic that receives only a brief mention in this study.

Section 2 briefly describes the model integrations and the data analysis procedure. In section 3, we consider the correlations of tropical Atlantic SST with ENSO and NNE Brazil precipitation. We find that the remote influence of ENSO contributes significantly to the dipole structure in the correlation between NNE Brazil precipitation and tropical Atlantic SST.

Section 4 addresses the issue of the positive heat flux feedback associated with tropical Atlantic SST anomalies. We find that during the boreal spring season, the remote effects of ENSO contribute significantly to the warming of tropical Atlantic SST, especially in the 10°–20°N latitude band. This process has the misleading appearance of a “positive” local feedback because a positive SST anomaly is associated with downward surface heat flux.

In section 5, we try to identify the atmospheric processes responsible for the remote and local interactions. We find that seasonal-to-interannual atmospheric variability in the tropical Pacific–Atlantic system is dominated by the interaction between two distinct sources of tropical heating: (i) the equatorial heat source in the eastern Pacific associated with ENSO and (ii) the off-equatorial heat source associated with SST anomalies in the Caribbean region. Section 6 briefly considers how variability in the tropical Atlantic may affect the tropical Pacific, raising the possibility of a two-way interaction.

2. Model integrations and data analyses

The atmospheric model used in this study is the latest version of the Community Climate Model (CCM3) developed at the National Center of Atmospheric Research (NCAR). It is a state-of-the-art AGCM incorporating a comprehensive suite of physical parameterizations (Kiehl et al. 1998). Global-scale features of the climatology and variability of CCM3 are documented by Hurrell et al. (1998) and Saravanan (1998). Chang et al. (2000) analyze the tropical Atlantic climatology of CCM3 integrations and find the simulations of surface fluxes and precipitation to be fairly realistic.

Three different ensembles of integrations were carried out using CCM3. Each ensemble consisted of five integrations, each 45 yr long, spanning the calendar years from 1950 to 1994. The five ensemble members were initialized with slightly different initial conditions to represent internal atmospheric variability. To minimize the “contamination” due to internal variability when identifying the atmospheric response to SST forcing, we simply average over the ensemble members.

The three ensembles are Global Ocean Global Atmosphere (GOGA): the observed monthly SST variability from 1950 to 1994 (Smith et al. 1996) was specified over the global ocean; Tropical Ocean Global Atmosphere (TOGA): observed SST variability was specified only over tropical oceans in the latitude belt 30°S–30°N and the climatological annual cycle of SST was specified everywhere else; and Tropical Atlantic Global Atmosphere (TAGA): observed SST was specified only in the Atlantic basin in the latitude belt 20°S–20°N. For the TOGA and TAGA integrations, the observed SST variability was linearly “blended” with the climatological annual cycle of SST over a 10°-wide latitudinal band to achieve a smooth transition. All integrations were carried out at the standard spatial resolution of CCM3: T42 spectral truncation in the horizontal and 18 levels in the vertical.

For some of our analyses, we will also use the surface pressure obtained from the National Centers for Environmental Prediction—National Center for Atmospheric Research (NCEP—NCAR) 40-Year Reanalysis project (Kalnay et al. 1996) during the 37-yr period (1958–94) that overlaps with the CCM3 integration time period. Note that this NCEP—NCAR data constitutes a much smaller sample than the 225 yr of data obtained from each of the model ensembles.

The monthly mean data from the model integrations was stratified into four seasons: September–November (SON), December–February (DJF), March–May (MAM), and June–August (JJA). Although all seasons were analyzed, our discussion will focus primarily on the MAM season, which shows the strongest evidence for the remote influence of ENSO in the tropical Atlantic and for the dipole correlation structure in SST (Curtis and Hastenrath 1995; Enfield and Mayer 1997; Uvo et al. 1998; Chang et al. 2000). We will present a few results for the DJF season, which also shows a significant ENSO influence.

We carry out simultaneous correlation and regression analyses using the seasonally averaged data. Linear trends in the data were removed by least squares fitting prior to correlation–regression analysis. We use a Student’s t test to assess the local statistical significance of correlation–regression patterns at the 95% level.

Simultaneous correlations are appropriate when considering the atmospheric response to SST forcing, which occurs on timescales shorter than a season. Lagged correlations are more appropriate if one is interested in the SST response to atmospheric forcing because of the delay in the response associated with the mixed-layer timescale. Since our AGCM experiments use prescribed SST, we use simultaneous correlation analysis. However, we did repeat some of our analysis using three-month lagged correlations, for example, the DJF ENSO signal correlated with the MAM tropical Atlantic response, and obtained similar results.
3. SST variability

We first examine the two well-known, nonlocal relationships associated with tropical Atlantic SST: the correlation with ENSO and the correlation with precipitation variability in the NNE Brazil region.

a. Relationship to ENSO

We use SST averaged over the Niño-3 region (5°S–5°N, 150°–90°W) as an index to represent ENSO. The regression between the Niño-3 index and tropical Atlantic SST during the MAM season is shown in Fig. 1. The regression was computed for the calendar years 1950–94 using SST from the reconstructed dataset of Smith et al. (1996). If one computes the lagged regression of SST for the MAM season against the Niño-3 index for the DJF season, the regression amplitudes are slightly stronger but the spatial pattern remains the same.

We see in Fig. 1 many of the features noted in the study of Enfield and Mayer (1997). The strongest and the most statistically robust relationship between ENSO and tropical Atlantic SST variability is found north of the equator in a broad zonal band centered around 15°N. This motivates us to define a northern tropical Atlantic (NTA) SST index, which is computed by spatially averaging SST anomalies in the latitude band 4°–20°N across the Atlantic basin (corresponding to the rectangular box shown in Fig. 1).

We will use the NTA index to characterize tropical Atlantic SST variability north of the equator. The regression values in the NTA region are positive, indicating that warm SST anomalies tend to occur during ENSO years. Although the regression amplitudes are stronger in the eastern part of the domain, the correlations are actually higher in the western part near the Caribbean (Enfield and Mayer 1997)

The regression values in the southern tropical Atlantic region are weakly negative. This is slightly different from the results of Enfield and Mayer (1997), who found weak positive correlations using a somewhat different analysis procedure. However, the correlations in this region have only marginal statistical significance, and this discrepancy may just mean that the correlations are very weak.

b. Relationship to NNE Brazil precipitation

The strongest evidence for the existence of a dipole mode of variability in the tropical Atlantic comes from the structure of the SST correlation with precipitation in the NNE Brazil region (Hastenrath and Heller 1977; Moura and Shukla 1981; Hastenrath 1984; Servain 1991). Additional evidence comes from empirical or-
thogonal function (EOF) analyses of tropical Atlantic SST, where a dipole mode often emerges as one of the dominant EOFs (e.g., Hastenrath 1978; Servain 1991). However, EOF analysis is a purely statistical technique and is not guaranteed to produce dynamically interpretable modes (North 1984). Some of the more recent studies have argued that the dipole EOF mode vanishes when the EOFs are rotated (e.g., Houghton and Tourre 1992; Dommengen and Latif 1999). EOF rotation is also just another statistical technique that tends to produce localized structures regardless of whether or not the localization is physically meaningful. Therefore, the strongest evidence against the existence of the dipole mode is the lack of a strong negative correlation between the northern and southern lobes of the dipole (Houghton and Tourre 1992).

The suite of GOGA, TOGA, and TAGA integrations allows us to investigate whether remote influences contribute to the so-called Atlantic dipole pattern. We averaged the MAM seasonal precipitation over the NNE Brazil region for the different ensembles and computed the squared correlations with tropical Atlantic SST (Fig. 2). The GOGA and TOGA integrations both show a dipole structure for the squared correlations during the MAM season quite similar to that seen in observations (e.g., Hastenrath and Heller 1977; Nobre and Shukla 1996). The similarity between the GOGA and TOGA integrations shows that extratropical SST anomalies do not play any significant role in these correlations. The squared correlations have roughly equal amplitudes, of the order of 0.4, in the northern and southern tropical Atlantic. Squared correlations for the other seasons (not shown) exhibit rather less symmetry between the two hemispheres.

The TAGA integrations, however, show a somewhat different correlation structure (Fig. 2c). The squared correlation in the northern tropical Atlantic drops from about 0.4 to 0.2 between the TOGA and the TAGA integrations. This means that remote tropical influences account for about half the covariance between NNE Brazil precipitation and SST anomalies in the northern tropical Atlantic. It can be shown through regression analysis that this remote influence is predominantly associated with ENSO.

It is well known that ENSO is associated with negative precipitation anomalies over NNE Brazil (e.g., Hastenrath et al. 1987). ENSO is also associated with positive SST anomalies in the northern tropical Atlantic (Fig. 1). The combination of these two effects leads to the enhanced correlations in the northern tropical Atlantic, as seen in Figs. 2a and 2b. Although the TAGA integrations have the same north tropical Atlantic SST variability as the TOGA integration, the correlations with NNE Brazil rainfall are weaker because of the absence of the remote influence of ENSO.

We conclude that the evidence for the existence of a truly dipolar mode of Atlantic SST variability is considerably weakened when the remote influence of ENSO is taken into account. However, the cross-equatorial gradient in the correlation remains strong even in the absence of ENSO forcing, as indicated by the TAGA integrations (Fig. 2c). This suggests that it is the atmospheric response to the cross-equatorial SST gradient and not the presence of a strong dipole mode in SST that affects NNE Brazil precipitation.

4. Surface heat flux variability

Surface heat flux forcing is believed to play an important role in determining tropical Atlantic SST variability (Carton et al. 1996; Chang et al. 1997). This is in contrast to the situation in the tropical Pacific, where the displacement of the thermocline associated with the dynamical adjustment to wind stress forcing is the dominant mechanism for SST variability. Part of the reason for this is that the Atlantic analog of the Pacific ENSO appears to be a damped oscillation and does not dominate the SST variability (Zebiak 1993). In this section, we examine the local and nonlocal relationships affecting surface heat flux variability over the tropical Atlantic.

a. Relationship to northern tropical Atlantic SST

One of the important issues with regard to surface heat flux variability is the positive correlation between SST and downward heat flux, discussed in the introduction. The strongest observational evidence for this is seen in the northern tropical Atlantic (Chang et al. 1997), especially during the MAM season. We would like to determine whether such positive correlations are evident in the CCM3 integrations and, if so, whether they are affected by the remote influence of ENSO. To quantify the local correlation between surface heat flux and SST, we use the NTA SST index, defined in section 3.

For the GOGA and TOGA integrations, the correlation between the NTA index and the downward surface heat flux during the MAM season shows significant positive values between 0° and 15°N, with mostly negative values elsewhere (Figs. 3a,b). This implies that there are regions where a positive SST anomaly is associated with a downward heat flux anomaly and vice versa, potentially representing a positive feedback.

For the TAGA integrations, however, the positive correlations are weaker and confined to a smaller region close to the equator and the negative correlations are stronger north of 15°N (Fig. 3c). This means that a significant portion of the positive correlation to the north of the equator seen in Figs. 3a and 3b is not due to local air–sea interaction but is associated with remote influences, namely, the effect of ENSO. This remote influence is strongly seasonal and is most pronounced during the MAM season.

Note that even in the TAGA integrations, there are indications of a positive feedback in the deep Tropics, equatorward of 15°N (Fig. 3c). Chang et al. (2000) an-
Fig. 2. Squared correlation (%) between tropical Atlantic SST and ensemble-averaged precipitation over northern Nordeste Brazil ($11^\circ -3^\circ S$, $46^\circ -38^\circ W$) for the GOGA, TOGA, and TAGA integrations (MAM season). Contour interval is 10%. Dashed contours imply that the correlations were negative before being squared. Rectangle in (a) denotes the northern Nordeste Brazil region over which the precipitation was averaged. Statistically significant squared correlations are shaded, with values greater than 30% having darker shading.
alyze this deep tropical positive feedback using a more sophisticated statistical technique and show that it is strongest during the DJF season. They also find the DJF season to be the dominant contributor to the year-to-year variability in the local response to tropical Atlantic SST anomalies.

b. Relationship to ENSO

To obtain more direct evidence for the effect of ENSO on the tropical Atlantic, we compute the regression between downward surface heat flux in the tropical Atlantic and the Niño-3 index. This regression is carried...
out for the ensemble-averaged difference between the TOGA and the TAGA integrations (TOGA–TAGA integrations). By differencing the two integrations, we eliminate the local response to tropical Atlantic SST anomalies and retain only the remote influence. Of course, one needs to assume that the atmospheric response to tropical Pacific–Atlantic SST anomalies is additive to justify this differencing procedure. As the subsequent discussion will show, we are able to assign dynamical interpretations to the regression patterns obtained from the TOGA–TAGA integrations, which provides some a posteriori justification for this assumption.

Differencing the GOGA and TAGA integrations yields similar results as those for the TOGA–TAGA integrations. Since all our results are quite insensitive to whether we use the GOGA or TOGA integrations, we will not present any further analyses of the GOGA integrations. We will henceforth use the TOGA–TAGA integrations to identify the remote effects of ENSO and the TAGA integrations to identify the local response to tropical Atlantic SST anomalies.

The regression pattern between the surface heat flux and the Niño-3 index was computed for both the DJF and the MAM seasons. This allows us to assess the remote influence of ENSO during its two most active seasons. During both seasons, the regressed heat flux patterns (Figs. 4a, 5a) show downward heat flux anomalies over much of the tropical Atlantic, implying that the warming associated with ENSO tends to spread into the tropical Atlantic, especially north of the equator. This process contributes significantly to the positive correlations between the NTA index and downward heat flux seen in Figs. 3a and 3b during the MAM season.

The sign of the heat flux anomaly pattern in Figs. 4a and 5a is consistent with the observed positive correlation between the Niño-3 index and tropical Atlantic SST anomalies north of the equator (Enfield and Mayer 1997). These results are, however, quite different from those of Latif and Barnett (1995), who analyzed a shorter period (1979–88) and emphasized the negative correlation between ENSO and tropical Atlantic SST.

There is some discrepancy between the simulations and observations in the southern tropical Atlantic. The AGCM integrations show downward heat flux anomalies associated with ENSO in both hemispheres (Figs.
where \( Q \) denotes the radiative flux and \( F \) denotes the sum of sensible and latent heat fluxes. In the Tropics, the dominant contribution to surface heat flux variability comes from the sensible and latent heat flux components, with the latter usually dominating. Radiative flux anomalies may sometimes be important, but they are usually quite small. Changes in \( F \) can arise from changes in the wind speed \( W \), from changes in the air-sea temperature difference \( \Delta T \) (defined as surface minus reference height value), or from changes in the air–sea specific humidity difference \( \Delta q \) (e.g., see Enfield and Mayer 1997).

Only the monthly averaged values of the variables \( Q, R, F, W, \) and \( \Delta T' \) were available to us from the CCM3 integrations. To compute the different contributions to changes in \( F \) using these variables, we make the following approximation:

\[
F = -cW\Delta T,
\]

where \( c \) is a constant. (The minus sign appears because we have chosen to define \( F \) to be positive downward.) Note that we would expect the latent heat flux to be proportional to \( \Delta q \). Because \( \Delta q \) values were not available to us, we have assumed that \( \Delta q \) is approximately proportional to \( \Delta T \), allowing us to directly relate \( F \) to \( \Delta T \).

If we let the overbar denote the climatological seasonal averages and the prime denote deviations from the averages, we may express the average flux \( \overline{F} \) and the linearized estimate of the perturbation flux \( F'_{\text{est}} \) as

\[
\overline{F} = c\overline{W}\Delta \overline{T} \quad \text{and} \quad F'_{\text{est}} = cW'\Delta \overline{T} + c\overline{W}\Delta T',
\]

where we have assumed that the nonlinear term \( W'\Delta T' \) can be neglected. Using (3) we may rewrite (4) as

\[
F'_{\text{est}} = F'_{W} + F'_{T},
\]

where
We focus on the distinction between the remote influence and how this remote influence is mediated by atmospheric variability over the tropical Atlantic. In this section, we analyze the effect of wind speed changes on the latent and sensible heat fluxes (e.g., Curtis and Hastenrath 1995; Carton et al. 1996; Enfield and Mayer 1997).

Figures 4b and 5b show the regression of \( F'_{wa} \) against the Niño-3 index during the DJF and MAM seasons. Note that these estimated regression patterns are quite similar to corresponding regression patterns for the actual heat flux anomalies (Figs. 4a, 5a), indicating that \( F'_{wa} \) captures the variability of \( H' \) rather well. We also computed the direct correlation between \( Q' \) and \( F'_{wa} \) at each grid point in the tropical Atlantic and found them to be highly correlated in most regions, with an area-averaged correlation of 0.75 during the MAM season. This a posteriori verification of the approximations [Eqs. (2)–(4)] gives us the confidence that \( F'_{wa} \) and \( F'_{T} \) can provide meaningful information despite the crudeness of the approximations used to evaluate them.

During the DJF season, \( F'_{wa} \) and \( F'_{T} \) both seem to contribute significantly to net heat flux anomalies (Figs. 4c,d). The \( F'_{wa} \) contribution dominates in the northeastern part of the tropical Atlantic whereas the \( F'_{T} \) contribution is stronger in the northwestern part and in the southern tropical Atlantic. The regression pattern associated with \( F'_{wa} \) (Fig. 4c) resembles the observed correlation pattern for speed anomalies associated with ENSO (Enfield and Mayer 1997).

We see from Figs. 5c and 5d that during the MAM season, the contribution from \( F'_{wa} \) dominates the regression pattern of \( F'_{sa} \). The contribution from \( F'_{wa} \) is weaker in amplitude. Over much of the tropical Atlantic, \( F'_{wa} \) and \( F'_{T} \) have the same sign; however, near the eastern boundary of the basin, they tend to cancel each other, with the contribution from \( F'_{T} \) dominating the net heat flux.

Our analysis and that of Chang et al. (2000) show that changes in the wind speed and changes in the air–sea temperature difference can both contribute to the surface heat flux anomalies. This conclusion is somewhat different from other studies of surface heat flux variability in the Tropics, which tend to focus only on the effect of wind speed changes on the latent and sensible heat flux (e.g., Curtis and Hastenrath 1995; Enfield et al. 1996; Enfield and Mayer 1997).

5. Remote versus local atmospheric response

In the previous section, we identified clear signatures of the remote influence of ENSO on surface heat fluxes over the tropical Atlantic. In this section, we analyze how this remote influence is mediated by atmospheric processes. We focus on the distinction between the atmospheric response to ENSO and the local response to SST anomalies in the northern tropical Atlantic. We do not consider the atmospheric response to SST anomalies in the southern tropical Atlantic because they are not strongly correlated with ENSO. We start by analyzing the variability in surface pressure, which is perhaps the best observed atmospheric variable. We then consider the surface wind and precipitation fields, both of which are closely related to the low-level atmospheric response to SST anomalies. Finally, we analyze the upper-level atmospheric response as represented by the 200-hPa winds. As in previous sections, we focus on variability during the MAM season.

a. Surface pressure

We start our analysis of atmospheric variability over the tropical Atlantic by comparing CCM3 simulations to observations. We use surface pressure from 37 years (1958–94) of NCEP–NCAR 40-yr reanalysis as our observational dataset for atmospheric variability. We regress surface pressure against the Niño-3 and NTA indexes, defined earlier. Figures 6a–d show the regression patterns for the NCEP–NCAR data and the TOGA–TAGA integrations. (The regression patterns for the GOGA integrations are quite similar.)

The observed ENSO signal in the surface pressure is known to be dominated by an east–west dipole pattern centered on the equator (e.g., Covey and Hastenrath 1978; Giannini et al. 2000). We see this east–west dipole in the NCEP–NCAR regression against the Niño-3 index and also in the TOGA regression (Figs. 6a,c). Another feature that is seen both in the model and in the observations is the low pressure center just north of the Caribbean region. The biggest differences between the NCEP–NCAR and TOGA regression patterns are seen over the North African region. It is not clear whether these differences are due to sampling errors associated with the much shorter observational record or to errors in the AGCM simulation.

Regressing the NCEP–NCAR and TOGA surface pressure data against the NTA index produces slightly different patterns (Figs. 6b,d). Although the east–west dipole is still present, the low pressure center over the Caribbean region is more prominent both in the model and in the observations. Again, there are notable differences between the model and the observations north of 20°N in the eastern half of the domain. The low pressure center near the Caribbean occurs considerably farther eastward and slightly northward in the observations, indicating that the model simulations may be deficient in simulating it.

The above comparisons between the model and the observations establish that CCM3 is capable of simulating some of the important observed features of atmospheric variability over the tropical Atlantic. However, these comparisons do not clearly distinguish between remote and local interactions. To make that dist-
tinction, we regress the surface pressure in the TOGA–TAGA and TAGA integrations against the Niño-3 and NTA indexes, respectively.

The surface pressure regression against the Niño-3 index for the TOGA–TAGA integrations (Fig. 6e) clearly shows the east-west dipole pressure pattern, but the low pressure center near the Caribbean is weaker than in the TOGA regression (Fig. 6c). The TAGA regression against the NTA index (Fig. 6f) shows a strong low pressure center slightly east of the Caribbean but no evidence of an east–west dipole pattern. Thus, we see that the east–west dipole is uniquely associated with the remote influence of ENSO. The local response to SST anomalies in the northern tropical Atlantic contributes to the Caribbean low-pressure center by shifting it southeastward. Since the NTA index and the Niño-3 index are correlated, the two features appear superposed in the NCEP–NCAR and TOGA regression patterns (Figs. 6a–d).

### b. Precipitation and surface winds

Next, we consider the precipitation and surface winds in the TOGA–TAGA and TAGA integrations, regressed against the Niño-3 and NTA indexes, respectively. The precipitation regression against the Niño-3 index shows a pattern having negative anomalies over much of the tropical Atlantic, with a prominent negative center off the coast of NNE Brazil centered around 5°S (Fig. 7a). This pattern also emerges as the second EOF of precipitation variability (not shown) in the tropical Atlantic region. The predominantly negative precipitation anomalies are consistent with the observed relationship between the ENSO and the precipitation in the tropical Atlantic sector (Enfield 1996; Hastenrath et al. 1987).

The surface wind regression against the Niño-3 index (Fig. 7a) shows southeasterly wind anomalies in the western equatorial Atlantic. This is consistent with the observed relationship between ENSO and the tropical Atlantic (e.g., Enfield and Mayer 1997) if one takes into account the fact that the observations will always include a correlated contribution from the NTA index as well (shown in Fig. 7b). The surface wind signal associated with ENSO is rather weak in the eastern part of the basin.

The precipitation regression against the NTA index shows a pattern with antisymmetric features about the equator (Fig. 7b); there is a band of positive precip-
Fig. 7. Regression of precipitation (contours) and 1000-hPa wind (vectors) for the MAM season (a) against the normalized Niño-3 index for the TOGA–TAGA integrations and (b) against the normalized NTA index for the TAGA integrations. Precipitation contour interval is 0.1 m yr⁻¹. Contouring/shading conventions as in Fig. 6.

tation anomalies north of the equator and a negative anomaly south of the equator off the coast of NNE Brazil, much like in the observations (e.g., Nobre and Shukla 1996; Enfield 1996). This meridional dipole pattern also emerges as the first EOF of precipitation variability (not shown).

To assess how well the above model simulated regression patterns correspond to observations, we also computed the regressions between the observed Niño-3 index for the MAM season and the observed precipitation (Xie and Arkin 1996) during the period of 1979–93 (Fig. 8a). Note that this analysis is based on a rather short data record and does not distinguish between local and remote effects, unlike the TOGA–TAGA model re-
Fig. 8. Regression of observed precipitation from the Xie–Arkin dataset (1979–93) for the MAM season (a) against the normalized Niño-3 index and (b) against the normalized NTA index after subtracting the regression with the Niño-3 index. Contour interval is 0.1 m yr$^{-1}$. Contouring/shading conventions as in Fig. 6.

We also computed the regression between the observed precipitation and the observed NTA index after subtracting the regression with the Niño-3 index shown in Fig. 8a to remove the ENSO influence. As seen in Fig. 8b, this regression pattern shows a dipolar precipitation anomaly straddling the equator off the coast of Brazil. Keeping in mind that this feature has very little statistical significance, we note that it is similar to the corresponding model regression pattern (Fig. 7b) but it is much more confined in the zonal direction north of the equator.
Continuing our discussion of the simulated regression patterns, we see from Figs. 7a and 7b that SST anomalies in the Niño-3 and NTA regions have a similar effect on NNE Brazil precipitation. We also know that ENSO excites positive SST anomalies in the NTA region during the MAM season (Fig. 1). The combination of these two effects can explain why the remote influence of ENSO results in enhanced correlations between NNE Brazil precipitation and SST in the northern tropical Atlantic (Figs. 2a,b).

Figure 7b also shows that SST anomalies in the northern tropical Atlantic affect precipitation north as well as south of the equator, leading to significant cross-equatorial surface flow in the regressed signal. Since the NTA index is not very strongly correlated with SST anomalies south of the equator, the precipitation anomaly near NNE Brazil and the associated surface wind anomalies must be responding to the cross-equatorial gradient associated with SST anomalies in the northern tropical Atlantic. Regression analysis (not shown) indicates that the cross-equatorial gradient associated with SST anomalies in the southern tropical Atlantic also induces surface wind anomalies in the Northern Hemisphere, but this effect is most pronounced during the SON season.

Overall, the GCM’s local response to tropical Atlantic SST anomalies (Fig. 7b) is stronger than the remote influence of ENSO (Fig. 7a) in the near-surface atmospheric variables. Some of the strongest surface wind anomalies over the tropical Atlantic tend to occur between 5°S and 5°N (Fig. 7). This is the region with strongest precipitation during the MAM season, associated with the southward excursion of the Atlantic intertropical convergence zone (ITCZ). This implies that the dominant mode of atmospheric response to tropical Atlantic SST anomalies is a meridional shift in the position of the ITCZ, as has been suggested by many earlier studies (e.g., Hastenrath and Heller 1977; Moura and Shukla 1981; Hastenrath et al. 1987; Nobre and Shukla 1996; Enfield 1996). Because the mean surface wind speed is quite small in the ITCZ region, wind speed anomalies could have a significant impact on the surface heat exchange through nonlinear boundary layer processes. Indeed, Chang et al. (2000) find that wind-induced changes in the surface heat flux play an important role in the deep Tropics.

c. Upper-level winds

Finally, we consider how the upper-level atmospheric flow in the GCM responds to ENSO and to SST anomalies in the northern tropical Atlantic. Figure 9 shows the regression of 200-hPa wind for the TOGA–TAGA and TAGA integrations against the Niño-3 and NTA indexes, respectively. The TOGA–TAGA regression against the Niño-3 index is characterized by a strong westerly anomaly over the equatorial Atlantic region (Fig. 9a). The strongest off-equatorial anomalies occur as a dipole straddling the equator in the eastern Pacific. This is the classic signature of the atmospheric response to an equatorial heat source located in the eastern Pacific (Gill 1980). This means that the teleconnection between the eastern tropical Pacific and the tropical Atlantic is explained by an anomalous Walker circulation (Kidson 1975). This also suggests that there is no need to invoke any extratropical teleconnection mechanism such as the PNA pattern, although a more thorough analysis of the time lags between the ENSO forcing and the tropical Atlantic response would be needed to confirm this.

The regression between 200-hPa wind and the NTA index for the TAGA integrations (Fig. 9b) shows a signal that is weaker and very different in structure from the ENSO signal seen in Fig. 9a. The most prominent feature is the strong anticyclonic flow centered east of the Caribbean region, very close to the surface low pressure center noted earlier (Fig. 6f). Once again, this corresponds to the signature of the atmospheric response to a heat source, but one that is centered off the equator in the Caribbean region (Gill 1980). There is also a secondary circulation feature centered over the Guinean coast of Africa.

We also computed the regression patterns corresponding to Figs. 9a and 9b for the DJF season (not shown). For the Niño-3 regression, we obtained a very similar pattern. For the NTA regression, the anticyclonic flow center north of the equator was considerably weaker and shifted farther eastward.

An important feature of both upper-level regression patterns shown in Fig. 9 is that they have a structure that is quite different from the surface-flow regression patterns (Fig. 7). For the surface flow, the local response to SST anomalies appears to dominate over the remote influence of ENSO whereas for the upper-level flow, the remote influence is stronger than the local SST forcing. Though the simple models of tropical heating, analyzed by Gill (1980), may describe the upper-level atmospheric flow quite well, it appears that the near-surface variability requires a somewhat different explanation.

6. Effect of tropical Atlantic variability on the tropical Pacific

The TAGA integrations also allow us to assess the possible influence of tropical Atlantic variability on the tropical Pacific. The regression of the surface wind against the NTA index (Fig. 7b) shows that SST anomalies in the northern tropical Atlantic produce positive precipitation anomalies and an associated surface-wind response of the order of 1 m s⁻¹ over the Pacific between 5°–15°N and 110°–80°W, during the MAM season. A similar feature is seen during other seasons of the year as well (not shown). This provides a mechanism by which the Caribbean heat source can affect tropical Pacific variability. There is some indication of this precipitation signal even in the observed precipitation regression (Fig. 8b), but it is not statistically significant.
Fig. 9. Regression patterns for 200-hPa wind during the MAM season (a) against Niño-3 index for TOGA–TAGA integrations and (b) against NTA index for TAGA integrations. Shading convention as in Fig. 6.

Note though that the influence of northern tropical Atlantic SST anomalies on the equatorial Pacific is very weak, suggesting that this feedback may not be very important for ENSO itself.

We also carried out a regression analysis between surface wind and SST anomalies in the southern tropical Atlantic (not shown) and found virtually no signal over the tropical Pacific. Presumably, the considerable zonal extent of the South American continent shields the tropical Pacific from the influence of SST anomalies in the southern tropical Atlantic.

7. Summary and discussion

Our atmospheric modeling study finds that the SST anomalies in the eastern tropical Pacific associated with ENSO have a significant remote influence on tropical Atlantic variability, as noted in many observational studies. The influence of extratropical SST anomalies is very small. This suggests that the remote influence of ENSO in conjunction with the local atmospheric response to SST anomalies can explain much of the variability in the tropical Atlantic region. The detailed spatial structure of the local atmospheric response to SST anomalies is analyzed in the companion study by Chang et al. (2000) using more sophisticated statistical techniques. Their findings are largely consistent with the results presented here.

Measured in terms of the net surface heat flux, the remote influence of ENSO as simulated by the GCM appears as a warming of the tropical Atlantic associated with the warming in the eastern tropical Pacific. The
surface heat flux anomalies over the tropical Atlantic associated with ENSO are caused by changes in the wind speed as well as by changes in the air–sea temperature difference. There is also a surface wind stress signal over the western equatorial Pacific, which creates a zonal seesaw pattern in the surface pressure (Kidson 1975; Covey and Hastenrath 1978; Giannini et al. 2000). The large-scale subsidence associated with this anomalous Walker circulation can explain the negative precipitation anomalies associated with ENSO and the surface heat flux anomalies that act to warm the SST. The upper-level atmospheric wind anomalies associated with this circulation show a large-scale structure that closely resembles the “classical” response to an equatorial heat source (e.g., Gill 1980). The surface wind anomalies, however, show a different structure, with much smaller amplitudes and spatial scales.

The upper-level structure of the local atmospheric response to northern tropical Atlantic SST anomalies closely resembles the idealized response to an off-equatorial heat source described by Gill (1980), with the heat source located in the Caribbean region. Once again, the surface wind response shows a somewhat different structure, with significant cross-equatorial flow over the western equatorial Atlantic, pointing to the importance of the cross-equatorial SST gradient [see Chang et al. (2000) for a more detailed discussion]. The response to this Caribbean heat source also has an impact on atmospheric flow over the northeastern tropical Pacific. This provides a possible, although weak, link for two-way interaction between the tropical Pacific and the tropical Atlantic.

The remote and local responses over the tropical Atlantic can occur simultaneously in observations, because of the correlation between ENSO and northern tropical Atlantic SST, making it difficult to distinguish between them. The local response to tropical Atlantic SST anomalies dominates the near-surface atmospheric flow, whereas the remote influence of ENSO dominates the upper-tropical flow. Although the Gill-type model works very well in describing the upper-tropical response, the near-surface response appears to be closely tied to the dynamics governing the surface convergence and the meridional location of the ITCZ. In this respect, the tropical Atlantic region is different from the equatorial Pacific region, for which the Gill-type model has been used successfully to model the surface winds associated with phenomena such as the ENSO (Zebiak and Cane 1987).

The link between ENSO and the tropical Atlantic is in many respects similar to the extratropical atmospheric “bridge” in the North Pacific (Alexander 1992; Lau and Nath 1996) in that the anomalous Walker circulation associated with ENSO excites SST anomalies in the tropical Atlantic. However, there is an important difference: tropical SST anomalies are more effective at exciting an atmospheric response than midlatitude SST anomalies. This means that this tropical atmospheric bridge could play an important role in extending the predictability associated with ENSO into the Central American–Caribbean region (Penland and Matrosova 1998). One could conceivably capture this effect by forcing an AGCM with prescribed SST in the tropical Pacific but coupling the AGCM to a mixed-layer ocean model in the tropical Atlantic region.

Understanding the remote influence of ENSO helps dispel some of the confusion surrounding the so-called Atlantic dipole mode. The primary evidence for the existence of the dipole structure comes from the correlations between NNE Brazil rainfall and Atlantic SST (Hastenrath and Heller 1977; Moura and Shukla 1981). Our analysis of the suite of AGCM integrations shows that in the absence of the ENSO signal these correlations become significantly weaker north of the equator; NNE Brazilian rainfall is more strongly correlated with SST anomalies in the southern tropical Atlantic than in the northern tropical Atlantic. This implies that variability that is truly local to the tropical Atlantic may have less of a dipole character than has been previously suggested. Recent hybrid modeling studies with better representations of stochastic atmospheric variability (Chang et al. 1999) also indicate that the SST evolution in the tropical Atlantic cannot be simply characterized as a standing dipole oscillation, even though the positive feedback is important for simulating realistic SST variability.

The positive correlation between SST anomalies and the downward surface heat flux (Chang et al. 1997) is also weakened during the boreal spring season when the effects of ENSO are removed, indicating that there is less of a positive feedback. This points to the well-known difficulty in inferring causality from simultaneous correlations. In the midlatitudes, forcing of the ocean by internal atmospheric variability leads to positive correlations between SST and the downward surface heat flux (e.g., Saravanan 1998; Frankignoul 1999). Our study shows that in the tropical Atlantic such positive correlations can arise from the remote forcing associated with ENSO. Therefore, one needs to be cautious about constructing statistical atmospheric models from simultaneous correlations not just in the midlatitudes, as pointed out by Frankignoul (1999), but even in tropical regions where remote effects may play a role.

However, even the TAGA integrations, which exclude the remote ENSO forcing, show some positive feedback in the atmospheric response to SST anomalies. This positive feedback is confined to the deep Tropics, that is, equatorward of 15° latitude, and is seen primarily
during the boreal winter and spring seasons. This deep tropical feedback is analyzed in the companion study by Chang et al. (2000), where it is shown that it arises from wind-induced changes in the surface heat flux. The positive feedback probably is associated with the cross-equatorial SST gradient and not with a dipole mode in SST.

Some of the important questions raised by this study are as follows.

1) Can one develop a simple atmospheric model for use in the tropical Atlantic region that is analogous to those used for ENSO studies (e.g., Zebiak and Cane 1987)? An important requirement of such a model would be that it captures the near-surface ITCZ dynamics and the Gill-type upper-level atmospheric response. Another requirement would be that it captures the surface wind response to the cross-equatorial SST gradient, which is a very important process in the tropical Atlantic.

2) What is the role of oceanic feedback in tropical Atlantic variability? An atmospheric modeling study by itself cannot capture all the effects of ENSO on the tropical Atlantic Ocean. Important effects such as the finite heat capacity of the mixed layer (Barsugli and Battisti 1998; Saravanan and McWilliams 1998) and the oceanic response to wind stress forcing can only be represented in a coupled model. Preliminary results from an AGCM coupled to a slab ocean model suggest that the thermodynamic feedbacks associated with the oceanic mixed layer play a significant role in determining the spatial and temporal characteristics of tropical Atlantic variability (Saravanan and Chang 1999).

3) What is the role of the Caribbean heat source in seasonal-to-interannual variability in the vicinity of the tropical Atlantic region? Our study suggests that the Caribbean heat source may be excited in two different ways: through the remote influence of ENSO and through variability that is local to the tropical Atlantic. Both of these excitation mechanisms could have important implications for seasonal predictability (Enfield and Mestas-Núñez 1999).

A cautionary note: some of the features that are seen in the CCM3 simulations, especially in the deep Tropics, are not well resolved at the T42 horizontal resolution. Higher-resolution studies are needed to simulate these features better. CCM3 is also deficient in its simulation of the precipitation anomalies associated with the Caribbean heat source. It is therefore very important to test the sensitivity of our results to the convective and boundary layer parameterizations in CCM3 and also to make intercomparisons with other GCMs.

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REFERENCES


