Looking for the role of the ocean in tropical Atlantic decadal climate variability.[1,2]

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Abstract

Ocean models are used to investigate how variations in surface heat fluxes and ocean heat transports contribute to variations of tropical Atlantic sea surface temperatures on decadal timescales. The observed patterns of variability, deduced from reanalyses of the National Centers for Environmental Prediction, are found to involve the ocean's response to variations in the strength of the northeast and southeast trades. Stronger trade winds are associated with anomalously cool surface temperatures. The trade winds and surface temperatures in each hemisphere appear to behave independently but each is associated with anomalous cross equatorial flow. A numerical model is used in an attempt to simulate this variability. The model is an ocean general circulation model coupled to a simple model of the atmospheric mixed layer and is forced by NCEP winds from 1958 to 1998. The model reasonably reproduces the observed variability. Analysis of the ocean model's mixed layer energy budget shows that, on decadal timescales, the surface temperature variability is forced by the changes in surface fluxes and is damped by changes in the ocean heat transport. The changes in ocean heat transport are dominated by the horizontal advection of anomalous temperatures by the mean meridional currents. **If advection of the mean SST field by anomalous currents is neglected then the history of observed surface temperatures can still be adequately represented. If advection of the anomalous SSTs by the mean circulation is also neglected then the model significantly overestimates the surface temperature anomalies but reproduces their temporal evolution.** In the more complete models, between $15°N$ and $15°S$, the changes in ocean heat transport are largely in phase with the changes in surface heat fluxes and SST. Evidence for ocean heat transport either leading or lagging development of surface temperature anomalies is weak in the deep tropics but appears more persuasive in the northern subtropics. Consistent with these findings, SST anomalies are largely stationary in the deep tropics but appear to propagate poleward in the northern subtropics. Nonetheless these results suggest that the role of the ocean in tropical Atlantic decadal climate variability is largely passive and damping. Differences with other models that show a more critical role for the ocean, and relevance to

reality, are discussed.

1. Introduction

It has been well established that the sea surface temperature (SST) of the tropical Atlantic Ocean varies in broad spatial patterns and on a variety of timescales. For example, the equatorial Atlantic has a weak pattern of variability that is analogous to the El Niño- Southern Oscillation phenomena of the tropical Pacific Ocean, but which is not self sustained (Zebiak 1993). Unlike the tropical Pacific Ocean, the tropical Atlantic Ocean also contains **patterns of variability that are centered off the equator** and which are characterized by basin scale warming and cooling of the subtropical oceans and a change in the cross-equatorial SST gradient (e.g. Nobre and Shukla 1996). This pattern of SST variability is associated with stronger (weaker) trade winds in the colder (warmer) hemisphere and anomalous flow in the lower levels of the atmosphere, across the equator, towards the anomalously warm hemisphere, or away from the anomalously cold hemisphere. It is also well correlated with precipitation variability over Northeast Brazil (Hastenrath and Heller 1977, Moura and Shukla 1981) and sub-Saharan West Africa (Lamb 1978a and b, Folland et al. 1986) as the Intertropical Convergence Zone shifts towards anomalously warm water or away from anomalously cool water.

Originally it was claimed that the subtropical SSTs of the two hemispheres vary out of phase giving rise to a dipole pattern (e.g. Moura and Shukla 1981). **However it has been questioned whether off-equatorial SST variability is anti-correlated between the hemispheres** (Houghton and Tourre 1992). Most recently, Rajagopolan et al. (1998) and Enfield et al. (1999) have concluded that the SSTs of the two hemispheres are not related to each other **and the significance of the dipole-like pattern in SST correlations with rainfall or winds is an implication that the cross-equatorial SST gradient is the key dynamical factor (see also Hastenrath and Greischar 1993)**.

The pattern of subtropical warmings and coolings is present in the tropical Atlantic on both interannual and decadal timescales. On interannual timescales this pattern can emerge as the response to externally forced changes in wind speed associated with the North Atlantic Oscillation (e.g. Seager et al. 2000) or ENSO (e.g. Curtis and Hastenrath 1995, Saravanan and Chang 2000, Giannini et al. 2000). Both these mechanisms primarily impact the subtropical North Atlantic. How the subtropical South Atlantic SST varies is not so clear (Venegas et al. 1997, 1998). The origin of **tropical Atlantic decadal** climate variations remains obscure. It is possible that there is no variability at longer than interannual periods other than that expected from a red noise process. However it has been frequently claimed that there is a statistically significant spectral peak at around the decadal timescale. For example Mehta (1998), Rajagopolan et al. (1988) and Tourre et al. (1999) found a 12 year spectral peak in a century long record of the cross-equatorial SST gradient.

Changes in surface fluxes of latent heat, driven by changes in wind speed, are the primary cause of off-equatorial tropical Atlantic SST variability (Carton et al. 1996, Seager et al. 2000). If the changes in wind speed are externally forced by the NAO or ENSO then this would be expected to provide for similar timescale climate variability in the tropical Atlantic. This is almost certainly the case, although the multiple influences, and the probability that local air-sea coupling also comes into play, makes the situation very complex. Further, it must be remembered that there is no known cause for the timescale of NAO variability **although there is evidence that it is linked to tropical SSTs on decadal timescales** (Rajagopolan et al. 1998, Robertson et al. 2000). It is probable that decadal variability of tropical Atlantic climate combines local interactions with the influences of similar timescale variability of the North Atlantic and tropical Pacific regions in a quite complex manner.

In the search for the cause of decadal variability of the Pacific and Atlantic, attention has turned to the ocean because of the longer timescales associated with ocean motions and heat transport. In the case of the tropical Atlantic, Huang and Shukla (1997) have argued that the changes in cross equatorial winds can create changes in upper ocean heat content, with a lower thermocline in the hemisphere to which the anomalous winds blow, and a shallower thermocline in the other hemisphere, which can then impact the SSTs. They also suggest that propagation of the heat content anomalies may cause a decadal oscillation. However, Carton et al. (1996), using a numerical model, and Wagner (1996a, 1996b), from a consideration of ship data, demonstrated that the off-equatorial decadal SST signal could primarily be explained in terms of surface flux variability alone. They also showed that, while the interhemispheric difference in heat content does vary on decadal timescales, it has little effect on the off-equatorial SST anomalies. **Dommenget and Latif (2000) have demonstrated that in four coupled GCMs SST anomalies centered at around $15°$ of latitude are produced as a result of variations in trade wind strength, that changes in ocean heat transport are not essential and that the spectrum of variability is indicative of red noise.**

In contrast others have presented arguments for the importance of ocean dynamics. Chang et al. (1997) and Xie (1999) have proposed, on the basis of model experiments, that the surface fluxes and winds act constructively in that the altered SST fields give rise to winds that change the surface fluxes in a manner that reinforces the SST field. Xie (1999) argues that a warm off-equatorial SST anomaly, **centered at around $15°$ of latitude**, will induce anomalous westerlies, and reduced latent heat loss, on its equatorward side and anomalous easterlies, and increased latent heat loss, on its poleward side. This causes an equatorward migration of the warm water while introducing an SST anomaly of the opposite sign on the poleward flank that moves equatorward and causes the original SST anomaly to change sign. Advection by the mean Ekman flow is essential in preventing SST anomalies that propagate rapidly, and unrealistically, to the equator.

Chang et al. (2000b) propose a more fundamental role for the ocean whereby changes in ocean heat transport oppose the effect of fluxes and introduce a long timescale that allows the coupled system to oscillate. In contrast to Huang and Shukla (1996) they emphasize the role of meridional advection of heat by ocean currents. Chang et al. explored an oscillation of this type that arises in an ocean general circulation model (GCM) coupled to a statistical atmosphere model. In order for the system to oscillate as hypothesized, the ocean heat transport must be phase shifted relative to the SSTs and surface fluxes. However,the exact causes of any phase shift, and the origins of a timescale for the oscillation, remain unclear.

Here we report on further efforts to locate the role of the ocean in tropical Atlantic decadal climate variability. We will use the Lamont ocean general circulation model (GCM) thermodynamically coupled to a simple model of the atmospheric mixed layer (AML) and dynamically forced by observed winds for the 1958 to 1998 period. A forced ocean GCM can never be used to explain the causes of variability that is either coupled or the result of the atmosphere forcing the ocean. However, with the correct experimental setup, it can be used to understand the role of the ocean in coupled or forced variability. The correct experimental setup properly accounts for the thermodynamic coupling at the ocean surface. Although coupled simulations are in many ways best suited to unraveling the causes of coupled variability, properly formulated forced ocean experiments have one great advantage: the simulated record of climate variability can be directly compared against that which actually occured.

Our ocean GCM-AML model computes the air temperature and air humidity thus allowing the surface fluxes to be determined internally. This is absolutely essential in the case where the ocean forces the atmosphere and, hence, air temperature and humidity anomalies are created by the SST anomalies (Seager et al. 1988, Seager 1989). It is also necessary in the case where the atmosphere forces the ocean because the atmospheric thermodynamic state is still established via coupled interactions between the atmospheric and oceanic boundary layers. In some ways our experimental design can be thought of as analogous to that where an atmospheric GCM is thermodynamically coupled to an ocean mixed layer but there is no dynamic coupling. It avoids the kind of problems that arise when SST forced atmospheric GCMs are used to simulate cases where the SST anomalies arose from the atmosphere forcing the ocean. For a discussion of this see Bretherton and Battisti's (1999) criticism of the recent SST forced atmospheric GCM simulations of Rodwell et al. (1999). As shown by Bretherton and Battisti (1999) a critical test of forced simulations is that they reproduce the correct relationship between SST and surface flux anomalies. This will be an important criteria for evaluating the realism of our ocean model simulations.

Here we build on previous work by simulating a longer period, with an improved atmospheric boundary condition that allows a better assessment of the role of surface fluxes, and then performing a careful analysis of the oceanic heat budget. We will look for the phase differences between SST, surface fluxes and ocean heat transport that Chang et al. (2000b) have argued to be important for supporting a self-sustained oscillation in tropical Atlantic SST. We will also look for the meridional arrangement of anomalies of SSTs and surface fluxes that allows equatorward propagation in the model of Xie (1999).

In what follows we begin by looking in the observational record for the dominant patterns of variability and their temporal behavior. We will then compare these to the modeled behavior. After satisfying ourselves that the model reliably reproduces the history of SST anomalies that occured in nature, we examine how anomalies in surface fluxes and ocean heat transport created the SST anomalies. We then break apart the change in ocean heat transport to see how meridional, horizontal and vertical advection contribute. We will also look to see how changes in ocean heat transport are phased relative to the changes in surface fluxes, the SST anomalies and the atmospheric circulation forcing. In the next section we describe the observed variability of the off-equatorial tropical Atlantic Ocean. We then follow by describing the ocean GCM-AML model and then present the results of the model simulations. This is followed by a presentation of simulations using two simple ocean models, one that only includes the mean ocean circulation and one that is a mixed layer model. A discussion of the results, and a comparison with the results of other models, follows and finally we offer some conclusions and suggestions for future work.

2. Observed decadal climate variability in the tropical Atlantic region

There are a number of ways to derive spatial patterns of climate variability from the observational record. If we are interested in how the patterns of SST, wind and surface flux variability are related, then a popular tool is singular value decomposition (SVD, Bretherton et al. 1992). Chang et al. (2000b) performed an SVD analysis using surface marine data. The first SVD mode has an SST pattern that shows anomalies of opposite sign north and south of the equator and covering the entire zonal extent of the basin. Anomalous winds blow from the cold hemisphere to the warm hemisphere and the surface flux anomalies are of the sign that would create the SST anomalies. The SST, wind and surface flux anomalies are all much larger in the northern than the southern hemisphere so this cannot be characterized as a true dipole. Nonetheless, to the extent that the hemispheres vary out of phase, this may **be the result of the combined analysis with winds: as argued by Enfield et al.**

(1999), if the latter depended on the cross-equatorial SST gradient one would expect the results to show some anti-correlation between the north and south even if the two regions do not vary together.

In order to derive the patterns of observed variability that the model needs to reproduce we decided to look first for the patterns of wind variability since these will be common to both the data and the wind-forced model. This was done using empirical orthogonal function (EOF) analysis. We used surface winds from the NCEP reanalysis for the period from 1958 to 1998 and between $30°S$ and $30°N$. We applied a five month running mean to emphasize the long timescales and used the data from the entire year. The first EOF is a northern mid-latitude mode with little impact in the deep tropics. The second and third EOFs separately describe variations of the northern and southern trades and have distinctly different time series, as expected if there is no sychroneity between the two regions. However neither of the wind patterns contains significant cross-equatorial flow although this is frequently claimed to be an important part of the observed variability. Again the lack of an equatorial signal may derive from the orthogonality requirement, which is not necessarily physical.

We checked to see if anomalous cross equatorial flow is associated with the strength of the northern or southern trades. We area averaged the zonal winds over the northern and southern tropical Atlantic between latitudes 10° and 30° and the meridional wind between $5°S$ and $5°N$. A five month running mean was applied to the time series of the area averaged winds. The time series of the northern zonal wind and the equatorial meridional wind have a correlation coefficient of 0.35 whereas the southern zonal wind and the equatorial meridional wind have a coefficient of only -.09. This suggests that variations in the strength of the north-east trades are indeed associated with cross equatorial flow but variations in the southeast trades are not. We also found that the variations of the northern and southern trades were not correlated.

Therefore, to avoid the problems imposed by spatial orthogonality requirements, we rotated the EOFs under the varimax criteria as in Houghton and Tourre (1992). In this case the first mode is unchanged and the second and third EOFs are also much the same as their unrotated counterparts except that the northern mode now contains significant cross-equatorial flow. The northern mode explains 13% and 11%, and the southern mode 15% and 10%, of the variance of zonal and meridional winds, respectively. It appears that the rotated EOFs describe the observed circulation variability better than either the unrotated EOFs or the SVD analyses of winds, SST and heat flux.

To determine how the wind patterns are related to the patterns of SST and latent and sensible surface fluxes, we regressed the NCEP reanalysis estimates of these quantities onto the time series of the rotated EOFs of the winds. The wind vectors, SSTs and latent plus sensible surface fluxes are shown in Figures 1 and 2. Stronger trades in each hemisphere are associated with cooler waters and cross equatorial flow into the other hemisphere. Wind anomalies are confined to only one hemisphere and the equator. SST anomalies are strong in the hemisphere with the wind anomaly and weaker, but of opposite sign in the other hemisphere. The surface fluxes, defined positive upward, are of the sign that creates the SST anomalies in the hemisphere where the wind anomalies are strong, but damp the SST anomaly in the other hemisphere. The time series of these EOFs, also shown in Figures 1 and 2, are distinct, with the northern mode showing interannual variability with some decadal variability, while the southern mode clearly shows strong multidecadal variability.

This analysis does not recover an equatorial ENSO-like mode. If we redo the same analysis but separately on the first half and second half of the calendar year, then the equatorial mode is recovered as the second mode of the latter season. The northern and southern off-equatorial modes appear only during their respective winter, and early spring, seasons. Since our focus here is on the off-equatorial decadal mode the analyses based on all months of the year, which captures both the northern and southern modes, is sufficient.

3. Model description

We use the Lamont ocean GCM (Visbeck et al. 1998). The GCM spans the Atlantic Ocean from $30°S$ to $73°N$ with a resolution of 2° by 2°, and 30 fixed vertical levels, 13 of which are in the upper 1000m. The model includes basin geometry and bathymetry consistent with the resolution. Temperature and salinity are restored to climatology at the northern and southern boundaries. The model includes a simple one and a half layer thermodynamic sea ice model, a bulk wind-driven mixed layer model, convective adjustment and isopycnal thickness diffusion. The low meridional resolution means we do not expect to reproduce the ENSO-like equatorial variability but anticipate that the off-equatorial variability will be adequately captured.

The ocean GCM is coupled to a simple model of the atmospheric mixed layer (AML) described by Seager et al. (1995). It represents the well-mixed layer that underlies the cloudy portion of the marine boundary layer (e.g. Augstein 1978, Betts 1976). It computes the air temperature and air humidity by balancing the surface fluxes, advection, atmospheric eddy transports, entrainment from above and radiation. **As mentioned in the Introduction, since the atmospheric temperature and humidity are so closely tied to the SST, specifiying them in an ocean model's heat flux boundary conditions ensures that the model will reproduce the observed SST. Computing the air temperature and humidity is essential if the SST is not to be overly constrained.** The ocean GCM-AML model has been used successfully in simulations of tropical climate (Murtugudde et al. 1996), climate change (Seager and Murtugudde 1997) and climate variability (Seager et al. 2000).

The ocean GCM-AML model is dynamically forced by NCEP reanalyzed surface wind stress and uses NCEP wind speed and direction in the AML component. The period covers 1958 to 1998 but we discard the first five years to allow the model time to adjust from the climatological initial conditions. We use International Satellite Cloud Climatology Project estimates of the surface solar radiation (Bishop and Rossow 1991) and cloud cover. The cloud cover is used in the computation of the longwave cooling of the surface according to a bulk formula (Seager and Blumenthal 1994). The solar radiation and cloud cover are held at their climatological, seasonally varying, values. Therefore only changes in surface wind stress, speed and direction can create SST anomalies.

When the model is forced by NCEP reanalyzed winds it produces significant errors in the modeled annual mean SSTs. This is in contrast to previous experiments where we used winds from European Center for Medium Range Weather Forecasts analyses or other products (e.g. Murtugudde et al. 1996) and appears to be related to the differences in the wind fields. Seasonal variations and anomalies about the incorrect mean are quite realistic but we nonetheless decided to apply a flux correction that ensured a realistic SST climatology. To derive the flux correction we integrate the model with seasonally varying, climatological, forcing and compute the surface flux required for the model SST to perfectly track the observed climatological mean SST. For the integration using NCEP forcing from 1958 to 1998 the model then uses this required climatological surface flux plus a flux anomaly. The flux anomaly is the difference between the flux computed using the observed climatological mean SST plus the modeled anomaly SST and the flux computed using just the observed clmatological mean SST. Details can be found in Seager et al. (2000). The equation that governs the model's SST anomaly, T', is therefore:

$$\frac{\partial T'}{\partial t} + OHT' = \frac{1}{\rho c_p H}\left[Q(\bar{T}_{obs} + T') - Q(\bar{T}_{obs})\right]. \quad (1)$$

Here OHT' is the anomalous **horizontal plus vertical** ocean heat transport and diffusion plus convective mixing **within the top model layer**, H is the depth of the top model layer, $Q(\bar{T}_{obs}+T')$ is the surface flux computed using the climatological observed SST, $\bar{T}_{obs}$, plus the modeled anomalous SST, and $Q(\bar{T}_{obs})$ is the flux computed using the observed climatological SST. Other symbols have their usual meaning. Note that the flux $Q(\bar{T}_{obs} + T')$ is influenced not only by SST anomalies but also by changes in wind speed and direction.

4. Simulation of decadal climate variability with the ocean GCM-AML model

Figures 3 and 4 show the modeled SST and surface heat flux anomalies regressed onto the time series of the rotated EOFs of the observed winds shown in Figures 1 and 2. Since the observed winds are common to both nature and the mdoel, comparison of Figs. 3 and 4 with Figs. 1 and 2 shows the extent to which the ocean model response to the wind field is comparable to that which **actually occured as deduced by our statistical approach**. The patterns associated with changes in the strength of the northeast trades (Figs 1 and 3) are quite well reproduced by the model. The locations and amplitudes of the cooling of the northern tropical ocean, and warming in the northwest, are realistic. The associated modeled flux anomalies are also very similar in pattern and magnitude with those estimated from the NCEP data. In the model, as in nature, increased fluxes are associated with cooler water. In both model and data there is anomalous warm water south of the equator, even though the anomalous wind forcing there is small. The model clearly overestimates the warming just south of the equator in the west which is probably due to the inadequate representation of the equatorial ocean in this low resolution model. In this region the surface flux anomalies warm the ocean in both model and data. At the same time, the model underestimates the warming in the cold tongue region of the eastern equatorial Atlantic, probably also due to inadequate resolution of the equatorial dynamics. Elsewhere, south of the equator, the observed flux anomalies damp the SST anomalies while the model fails to produce coherent patterns of flux anomalies.

Figures 2 and 4 show the patterns associated with variations in strength of the southeast trades. The model reproduces the cooling south of the equator that goes along with increased trade wind strength but overestimates the SST anomalies. Again, both data and the model show that the SST anomalies south of the equator are produced by the variations in the surface fluxes. North of the equator, except for a narrow strip near the equator and along the South American coast, the model **and observations disagree**. The wind forcing in this region is weak and the observed flux anomalies damp the SST anomalies. It is not clear how these northern anomalies, associated with changes in the southeast trades, originate or how significant they are. The **most likely explanation, hinted to by the flux-SST relationship, is** that we are looking at the damping during summer of SST anomalies created during the winter.

The comparison of spatial patterns indicates that the model successfully reproduces the dominant patterns of the ocean's response to the changing winds bf in the hemisphere where SST is directly related to local wind variations. To understand the response we need to determine which processes are responsible. For both the northern and southern modes the fields of winds, fluxes and SST are quite zonally symmetric. Therefore, it is reasonable to zonally average the fields and look at how the zonal means evolve in time as a function of latitude. Chang et al. (2000b) used this approach and we will follow their procedure to examine how changes in fluxes and ocean heat transport influence the time evolution.

5. Causes of modeled decadal climate variability in the ocean GCM-AML model

To examine the causes of the decadal variability we have plotted zonal means of the anomalies of SST, the surface heat flux and the ocean heat transport. The latter includes the zonal, meridional and vertical advection and is integrated down to the mixed layer depth. Integration down to the mixed layer depth eliminates terms associated with wind driven and convective mixing within the mixed layer. Therefore, the sum of the surface heat flux and the ocean heat transport, together with a smaller contribution from diffusion (which always opposes SST changes and sometimes is as large as a quarter of the SST tendency) , equals the tendency of the mixed layer heat content. To emphasize the decadal timescale changes we smoothed all the fields with two passes of a 36 month running mean which effectively removes all variability with periods less than eight years.

We also computed the zonal mean of the observed SST anomaly, filtered the same way, and this is shown in Figure 5. The latitudinal range of this, and subsequent plots, was chosen to allow a direct comparison to the corresponding figures in Chang et al. (2000b). The SST anomalies are centered at around $15°N$ and $15°S$. There is no clear indication that the SST histories of the two hemispheres are related or that there is any meridional propagation or that SST anomalies, **centered at around** $15°N$, are systematically accompanied by opposite sign anomalies on their poleward flanks **north of** $15°N$ (as occurs in Xie's (1999) model). We also computed latitude-time plots of the surface fluxes using the NCEP reanalyzed SSTs, winds, air temperature and humidity and a bulk formula. Their behavior bears no relationship to the SST tendencies and is dominated by trends. The same problem occurs if we use the actual fluxes provided by NCEP or if we use da Silva's fluxes based on ship data (DaSilva et al. 1994). It is likely that the small flux anomalies, less than $5Wm^{-2}$, associated with decadal variability are much smaller than the noise and bias in the fluxes estimated from observations and cannot be resolved.

Figure 6 shows the modeled anomalies of SST, surface fluxes and ocean heat transport. The model does a credible job of reproducing the variations of the zonal mean SSTs. Certainly there are major errors off the equator before 1965, but from then on the model reproduces the cycles of warming and cooling with the exception of the southern hemisphere cooling centered on 1977. The simulation is generally more realistic in the northern hemisphere than to the south of the equator. The model also creates an equatorial cold event around 1981 which does not occur and, generally, the model SST anomalies are too large. Despite these problems we believe the agreement is sufficient for the processes that determine the modeled variability to be relevant to what occured in nature.

It is clear that the modeled surface heat fluxes match the SST **variability** quite well. Almost all the coolings and warmings of the SST have their surface flux counterpart in the sense of the atmosphere forcing the ocean. The exceptions are in the equatorial regions where the warming before 1965, and the cooling around 1980, were damped by the surface flux anomalies. **The SST and surface flux variability are almost in phase with only a weak indication of the surface fluxes leading the SSTs. We will return to why this is so later.** The ocean heat transport, though generally smaller than the surface flux, is also important. The change in ocean heat transport is almost always of the opposite sign to the change in surface heat flux. This indicates that the ocean transports are damping the SST anomalies created by the surface fluxes. Indeed, south of the equator, changes in ocean heat transport almost entirely cancel out the changes in the fluxes, as in Chang et al. (2000b). Equatorward of $15°N$ and S the changes in ocean heat transport are almost in phase with the changes in the surface fluxes and SST. There is little evidence of the ocean dynamics introducing a lead or lag or of meridional propagation. There may be a slight hint of weak poleward propagation of SST and and ocean heat transport anomalies after 1975. In contrast, further north, anomalies of SST and ocean heat transport appear to propagate poleward with changes in the ocean heat transport lagging those of the SST. The poleward propagation is not evident in the observed SST history (Fig. 5).

Our previous work has demonstrated that in the trade wind regions the surface flux variability is associated with changes in wind speed, rather than direction, and that the latent term dominates (Seager et al. 2000). What causes the changes in ocean heat transport? To look at this we broke the anomalous ocean heat transport into its constituent parts using monthly mean values:

$$\rho c_p (H_m u T_x)' = \rho c_p H_m' (\bar{u} \bar{T}_x) + \rho c_p H_m (\bar{u} T_x' + u' \bar{T}_x + u' T_x'), \tag{2}$$

$$\rho c_p (H_m v T_y)' = \rho c_p H_m' (\bar{v} \bar{T}_y) + \rho c_p H_m (\bar{v} T_y' + v' \bar{T}_y + v' T_y'), \tag{3}$$

$$\rho c_p (H_m w T_z)' = \rho c_p H_m' (\bar{w} \bar{T}_z) + \rho c_p H_m (\bar{w} T_z' + w' \bar{T}_z + w' T_z') \tag{4}$$

Primed quantities denote departures of the monthly mean from its climatological value, denoted by an overbar. Total values, anomaly plus climatology, have no subscript or superscript. H_m is the mixed layer depth. The cross terms were found to be small and the zonal terms were also smaller than the meridional and vertical terms. The first terms on the right hand side, which involve changes in mixed layer depth, were also found to be small. In Figure 7 we show the time filtered and zonal averaged terms $\rho c_p H_m \bar{v} T_y'$, $\rho c_p H_m v' \bar{T}_y$, $\rho c_p H_m \bar{w} T_z'$ and $\rho c_p H_m w' \bar{T}_z$, each of which make some significant contribution to the mixed layer temperature tendency.

On the equator the vertical term $\rho c_p H_m w' \bar{T}_z$ is the largest. This term corresponds to the anomalous winds upwelling the mean temperature gradient and it leads equatorial SST anomalies. The term $\rho c_p H_m \bar{w} T_z'$ strongly damps the SST anomalies as expected if the change in vertical temperature gradient is driven by the change in SST. This is in contrast to interannual variations in the Pacific (Seager 1989) and Atlantic (Zebiak 1993) where thermocline displacements cause changes in T_z' that can create SST anomalies. The time filtering has removed variability with timescales typical of the equatorial dynamics so this might be expected.

Although vertical terms are important near the equator, off the equator it is obvious that the $\rho c_p H_m \bar{v} T_y'$ term alone accounts for most of the anomalous ocean heat transport. Chang et al. (2000b) also noticed that this is the most important term and Xie (1999) suggests that the presence of this term prevents rapid equatorward propagation of SST anomalies.

Imagine there is a warm SST anomaly off the equator. $\bar{v}$ is poleward at all latitudes so $\bar{v}T'_y$ cools on the equatorward side of the SST anomaly and warms on the poleward side. Since $\bar{v}$ decays away from the equator, it is the damping on the equatorward side that dominates.

The $v'\bar{T}_y$ term is much weaker than $\bar{v}T'_y$ but also tends to damp the SST anomalies. It appears that v' is determined as an anomalous Ekman flow in response to anomalous zonal winds. Increased trade wind strength drives an anomalous poleward flow that warms. Since the increased trade wind strength cools the SST by increased surface fluxes the anomalous Ekman heat transport is a damping term. (In regions of mean westerlies, increased wind speed forces an equatorward flow that amplifies the SST change due to the fluxes (Carton et al. 1996, Seager et al. 2000)). The anomalous Ekman flow is established instantaneously so this term does not lead or lag the change in SST forced by the change in surface fluxes. The term associated with the mean meridional flow also will vary in phase with the SST as long as the SST anomalies do not propagate meridionally (as they appear not to). Since, in the model the SST changes in phase with the surface fluxes, then the total heat transport shows no lead or lag relationship with the SSTs or fluxes.

It is possible that the zonal averaging does not do justice to the role of ocean heat transport and that in some regions it plays a more active role. To see if this is so we regressed the model's anomalous ocean heat transport onto the time series of the rotated EOFs of the wind forcing. The patterns of ocean heat transport, together with the anomalous winds and the SSTs, are shown in Figures 8 and 9. The dominant signal in the ocean heat transport is the heat advection by the mean meridional currents which is located primarily in the hemisphere where the wind forcing is. However, west of Angola and Morocco, equatorward flow is associated with increased cooling by the ocean heat transport. This probably indicates changes in the rate of upwelling along the coast as well as advection of cool waters westward. Both Huang and Shukla (1997) and Carton et al. (1996) have observed this signal in their ocean model simulations. Changes in coastal upwelling and offshore advection are probably responsible for some of the observed SST changes in these regions, which are quite well represented in the model, and less well so in the simple models below that do not allow changes in the ocean circulation. This dynamical impact on the SST is limited to areas quite close to the African coast.

6. Simulations of climate variability with simple ocean models

a. Simulations with a mean ocean circulation model

We have shown that the changes in the ocean heat transport are primarily associated with advection by the mean circulation. It, therefore, should be possible to reproduce the observed variability of SST with the ocean GCM-AML model if we hold the wind stresses fixed at their climatological seasonal cycle, thus not allowing changes in the wind driven circulation. The AML component of the model retains the real time-varying wind speed and direction so the historical winds will still impact the ocean via the surface fluxes.

Figure 10 shows the zonally averaged and time-filtered anomalies of SST, surface heat flux and ocean heat transport for this case. It is evident that the mean circulation model does an excellent job of reproducing the SST variability of the full ocean GCM-AML model. The equatorial region is an exception where the mean circulation model fails to reproduce the warming before 1965 or the (apparently erroneous) cooling around 1980. As already mentioned, these SST changes were forced by changes in the equatorial zonal winds that induced anomalous upwelling. Off the equator the differences between the ocean GCM-AML model and the mean circulation model are quite subtle and not systematic. Neglect of the advection by the anomalous currents variously leads to stronger or weaker SST anomalies but does not cause any change in the phase relationship between the SST, surface flux and ocean heat transport. This is consistent with the anomalous currents (which we ignored in this calculation) being Ekman drifts that are established instantaneously by the wind forcing.

b. Simulations with a mixed layer model

A further simplification is to ignore the change in ocean heat transport entirely. In this case at each point we specify the seasonal cycle of mixed layer depth to be that from the full ocean GCM-AML model. The ocean heat transport is held at its diagnosed climatological, seasonally varying, values. The surface fluxes evolve as usual using the historical wind speeds and directions and are the only term that can create SST anomalies.

The zonally averaged, time-filtered, anomalies of SST and surface fluxes are shown in Fig. 11. The mixed layer model does an excellent job of reproducing the temporal history of the off-equatorial SST anomalies seen in the ocean GCM-AML model. It's equatorial simulation is as poor as that of the mean circulation model for the same reasons. However, the mixed layer model produces SST anomalies that are much larger than those in the ocean GCM-AML model or those observed. Also the surface flux anomalies are smaller than those in the ocean GCM-AML model. Both these differences arise from neglect of the advection by the mean circulation. Since the mean advection damps the SST anomalies, when it is neglected the SST grows only limited by the ability of the changing SST to reduce the flux anomaly that is driving the SST change. Consequently the SSTs become larger than observed and the flux anomalies become smaller. The mixed layer model also ignores temporal variations in the mixed layer depth and the temperature of entrained water which will lead to additional errors, though these are evidently not overwhelming.

The phase relationship between the surface fluxes and the SSTs is different to that in the models that retain ocean heat transports. In the mixed layer model maximum surface flux anomalies clearly precede maximum SST anomalies. The mixed layer model faithfully reproduces the timing of the observed SST anomalies but considerably overestimates their amplitude. This suggests that atmosphere models coupled to mixed layer models may be useful in some cases. However neglect of the mean ocean circulation does lead to significant errors in the amplitude of the SST variability which might have important consequences in coupled simulations.

7. Summary and discussion

We have presented simulations of the decadal variability of tropical Atlantic SSTs for the period of 1958 to 1998. We used a complete ocean GCM, a mean ocean circulation model and a mixed layer model, each coupled to a simple atmospheric mixed layer model so that the surface flux variability is determined internally. The combined models are forced by the history of the surface wind speed and direction as provide by NCEP reanalyses. The surface solar radiation and cloud cover were assumed to remain at their seasonal climatological cycle.

The model's SST variability was compared to that observed. Rotated EOFs of the surface wind field, which is common to the observations and the model, reveal separate modes describing variations in the strength of the northeast and southeast trades. The patterns of NCEP SST and surface flux anomalies that are associated with the wind patterns were derived by regression. In each hemisphere strengthened trades are associated with increased latent plus sensible heat loss from the ocean and cool SSTs. The time history of these patterns shows both interannual and decadal variability.

The same analysis was performed using the SSTs and surface fluxes produced by the ocean GCM-AML model. The model does a fair job of reproducing the SST and flux anomalies in the hemisphere where the wind forcing is located while, as might be expected, significant differences occur in the other hemisphere where the forcing on the ocean is small or nonexistent. We then sought to understand the causes of the SST variability. Following Chang et al. (2000b) we time-filtered the observations and the model results to remove variations with periods less than about eight years. We also zonally averaged the observations and model results since the patterns of climate variability are basin wide and vary little with longitude. We then examined latitude-time plots of the observed and model SST anomalies, and the modeled surface flux and ocean heat transport anomalies.

The picture that emerges is very simple. The off-equatorial SST anomalies are driven by the changes in surface fluxes that are associated with changes in the strength of the northeast and southeast trade winds. The changes in ocean heat transport are quite large and in some places comparable to the changes in surface fluxes. However, off the equator, the changes in ocean heat transport always oppose the changes in surface heat fluxes. Hence the ocean heat transport damps the SST anomalies that are created by the surface heat fluxes. In these experiments, warm (cold) off-equatorial SST anomalies are overlain by anomalous westerlies (easterlies) everywhere. We do not see the arrangement of winds and SST anomalies described by Xie (1999), and which was discussed in the Introduction. Therefore, we do not find evidence of his proposed wind-evaporation-SST feedback.

The changes in ocean heat transport, off the equator, are dominated by the advection of the anomalous SST by the mean meridional circulation. This agrees with and confirms the results of Chang et al. (2000b). For example, stronger trades increase the surface heat loss and cool the ocean and, at the same time, advection of the anomalous SSTs by the mean meridional currents will warm on the equatorward side of the latitude of the maximum SST anomaly and cool on the poleward side. This pattern of advection therefore damps the SST on the equatorward side but can amplify the SST on the poleward side. Since the strength of the mean meridional currents decreases away from the equator, the damping effect dominates. The advection of the mean SSTs by the anomalous meridional current also tends to damp the SST anomalies. The anomalous currents are established instantaneously as anomalous Ekman drifts. In the case of strengthened trades, there is anomalous poleward flow and advective warming. This term is much smaller than the mean circulation term.

Because the role of the ocean is so simple, it was possible to reproduce the SST variability of the full ocean GCM-AML model in a model in which the wind stress was held at its climatological seasonal cycle. Off the equator the history of anomalies of SST, surface fluxes and ocean heat transport were very similar to those of the full ocean GCM-AML model with no systematic differences. However, the SST anomalies produced by a mixed layer model with no change in ocean heat transport are much larger than those in the full model or those observed. This shows that the damping of SST anomalies by the mean meridional currents is an important effect which should not be ignored.

This analysis suggests that decadal variability of off-equatorial tropical Atlantic SST anomalies can be described by the equation:

$$T'_t + \bar{v}T'_y = -Q'/(\rho c_p H). \tag{5}$$

Q' is the surface flux anomaly. The flux anomaly is dominated by the anomalous latent heat flux and can be written as:

$$Q' = \rho_a L c_E (1-\delta)(\bar{U} q'_s + U' \bar{q}_s), \tag{6}$$

where ρ_a is the air density, L is the latent heat of evaporation, c_E is an exchange coefficient, $\delta = q_a/q_s$ with q_a equal to the air specific humidity and q_s equal to the saturation specific humidity at the SST, U is the surface wind speed and overbars denote means and primes denote perturbations. We have assumed that the relative humidity, which is approximately equal to δ, remains fixed. If we also assume that $q_s' = (\partial q_s/\partial T)_{\bar{T}} T'$ then we can rewrite the SST anomaly equation as:

$$T_t' + \bar{v} T_y' + a\bar{U} \left(\frac{\partial q_s}{\partial T} \right)_{\bar{T}} T' = -aU'\bar{q}_s, \tag{7}$$

where $a = \rho_a L c_E (1-\delta)/(\rho c_p H)$. The third term on the left represents the ability of the SST to adjust to surface flux variations associated with changes in wind speed, the latter represented by the term on the right hand side. The timescale for SST adjustment is typically about 200 days and is much shorter than the timescale of the decadal SST tendency.

There is little evidence for meridional propagation of SST anomalies either in our models or in observations. In the absence of propagation then the anomalous ocean heat transport ($\bar{v}T_y'$) will vary in phase with the SST anomaly. If the SST and the anomalous ocean heat transport adjust rapidly to the wind forcing then the time tendency in Eq. (7) is small and the anomalies of SST and ocean heat transport will lag behind the anomalous surface flux by only the short time it takes the SST to respond to wind forcing. In this case the surface flux anomalies are almost entirely balanced by the change in ocean heat transport. This appears to well describe the results with the ocean GCM and the mean circulation model. In contrast, when the ocean heat transport anomalies are neglected, then the SST anomalies must lag the surface flux anomalies and the two fields are almost in quadrature. This describes the results of our mixed layer model.

In contrast to our results, in the hybrid coupled model of Chang et al. (2000b) the anomalous advection by the mean meridional current clearly lags the SST which, in turn, lags the surface heat flux. **These phase relationships may be essential in allowing a self sustained oscillation of the winds and the SST. There are several differences**

between our model and that of Chang et al. For example they use a statistical model to derive the surface flux anomalies as opposed to our use of the AML model. However the fact that their SST anomalies propagate meridionally may be crucial in allowing a self-sustained oscillation. Poleward propagation causes the anomalous ocean heat transport to lag the SST anomalies because, when T' goes to zero, $\bar{v}T'_y$ remains nonzero. The mean meridional advection of anomalous SST might be able to cause poleward propagation because it damps the SST anomalies equatorward of the latitude of maximum anomaly and amplifies poleward. But we must stress that it is hard to see poleward propagation in the observed SST record although we must also admit that the record is short and contains many inaccuracies. Future work will have to resolve why SST anomalies propagate meridionally in the Chang et al. (2000b) hybrid model but do not in our GCM and which result is more realistic.

8. Conclusion

This work has shown that the decadal variability of tropical Atlantic SSTs can be explained in a very simple way as the response to variations in the surface fluxes forced by variations in trade wind strength. The SST responds rapidly so as to reduce the surface flux anomaly in an attempt to restore equilibrium. Consequently, on decadal timescales, the surface fluxes and the SST are almost in phase. The ocean heat transport provides an important damping. In the deep tropics the changes in ocean heat transport are in phase with the changes in SST. This is expected because they are dominated by advection by the mean meridional currents and any meridional propagation of SST anomalies is weak. The lack of any phase difference limits the ability of changes in ocean heat transport to cause oscillatory behavior. The mechanism by which ocean dynamics can cause an oscillation proposed by Huang and Shukla (1997) does not appear viable. They suggest that off-equatorial upper ocean heat content anomalies propagate around the Atlantic basin and can influence the SSTs. We find no evidence for off-equatorial SST anomalies being influenced by subsurface thermal anomalies except close to the African coast. It may be that upper ocean heat content anomalies do propagate around the basin (indeed we did not even look for this) but, to the extent that they do not influence the SSTs, they are irrelevant to climate variability.

It may be premature to conclude that the ocean's role in tropical Atlantic decadal variability is purely passive. In the hybrid model of Chang et al. (2000b), SST anomalies propagate meridionally and introduce a phase lag between the ocean heat transport and the SST and the surface heat flux. This appears to allow oscillatory behavior. It is possible that our model fails to show these phase lags because the simulated period is too short or because of model errors **or the forcing data is inadequate**. However, we note that it is even harder to see propagation in the observed record of SST anomalies but this may again be because of too short of a record.

Nonetheless, since our ocean model simulations find no evidence for an active role for the ocean, we are left to wonder what might cause oscillatory behavior. One possibility is that there actually are no oscillating modes in the tropical Atlantic. In this case low frequency climate variability arises in the ocean's ability to integrate atmospheric noise. On the other hand it is reasonable to suppose that the atmospheric circulation responds to the tropical SST anomalies. For example cool water in one hemisphere might shift the Intertropical Convergence Zone towards the other hemisphere. Such changes in atmospheric circulation will cause changes in surface wind speed that then might influence the SSTs in a manner that reinforces the original pattern. If upper ocean thermal anomalies can persist year to year, perhaps below the summer mixed layer and then re-emerging in winter, this could explain some year-to-year persistence of SST and atmospheric circulation anomalies. Of course this mechanism cannot provide for an oscillation with a distinct time period and, if there is a preferred period, then, according to this theory, it would have to come from outside the tropical Atlantic (e.g. Xie 1999).

It is clear that attempts to explain decadal variability of the tropical Atlantic need to determine how the atmosphere responds to SST anomalies. While the atmosphere creates the SST anomalies, does the subsequent atmospheric response involve changes in the surface fluxes that reinforce the original SST anomaly? Some model studies have shown that the atmospheric response does cause changes in surface fluxes that can reinforce the SST changes (e.g. Chang et al. 2000a). However, the areas over which this coherent interaction occurs are limited. Other model studies find no evidence of an amplifying atmospheric response (Sutton et al. 1999). However, these studies were done with atmospheric GCMs forced by observed SSTs. This experimental arrangement is fraught with problems in the case where the atmosphere is actually forcing the ocean (Bretherton and Battisti 1999) and the results obtained may be misleading. It also must be remembered that the tropical Atlantic is strongly influenced from outside, both by the higher latitude Atlantic and the the tropical Pacific, and decadal climate variability in these regions leave their imprint on the tropical Atlantic.

Finally we need to mention some caveats concerning this work. The simulations do not perfectly track the observed SSTs. There are several possible reasons for this. Differences in the magnitude of SST anomalies may easily be explained in terms of errors in the modeled ocean mixed layer depth. However, in some regions of the domain, most notably south of the equator, there is very little data and the NCEP winds and SSTs could easily be in error. It is also possible that the model is missing some important processes. For example, we ignore changes in solar radiation and cloud cover. Reliable estimates of cloud cover and surface solar radiation are being produced by the International Satellite Cloud Climatology Program (Bishop and Rossow 1991, Rossow and Schiffer 1991) and, as the record becomes longer, this will allow an assessment of how cloud and solar radiation variability impact the SSTs. Sutton et al. (1999) have argued that changes in the locations of deep convective cloud cover greatly impact the tropical Atlantic SSTs. It is also likely that changes in the coverage of low level stratus and trade cumulus clouds can impact the SST. Further, our model uses a coarse resolution that poorly resolves dynamical processes near the equator and coasts. In the latter region significant cross-equatorial heat transport occurs amongst a very complex circulation (e.g. Schott et al. 1998). In that our model reproduces the main features of the decadal variability of off-equatorial SSTs, this suggests that resolving the boundary currents in the coastal regions is not important for this aspect of tropical Atlantic climate variability. However, this certainly needs to be checked with a high resolution ocean model.

In the future we plan to examine the role of clouds in SST variability and to perform experiments with higher model resolution. Despite these caveats we do not think that the fundamental conclusion will alter. We began by looking for the role of the ocean in tropical Atlantic decadal climate variability and our results suggest that it is quite limited. Only advection by the mean ocean circulation appears to be critically important and the most obvious effect of this is to damp SST anomalies created by the surface fluxes. However we are not yet ready to exclude the possibility that even this limited role for the ocean may be capable of introducing important leads and lags between the SST, surface fluxes and ocean heat transport that sustain oscillatory behavior, even though we were unable to find evidence of such behavior in this forced ocean GCM experiment. However it is clear that the dominant atmosphere-ocean interactions that do occur primarily involve winds, surface fluxes and the ocean mixed layer. Here we have demonstrated how the changing strengths of the trade winds impact the SSTs. Further understanding of the causes of decadal variability requires a more complete understanding of how tropical Atlantic SST anomalies impact the local winds and whether this can provide for coupled interactions between the SSTs, surface fluxes and the atmospheric circulation capable of explaining decadal variability.

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Figure Captions

Figure 1. The second rotated EOF of NCEP surface wind anomalies together with associated SST and surface flux anomalies, also from NCEP, derived by regression onto the time series of the wind EOF. The winds are shown as vectors, the SSTs as colors, with the color bar in Kelvin at the right, and the surface fluxes as contours with the contour interval being $1Wm^{-2}$. Surface fluxes are defined positive if they cool the ocean. The time series is shown below with the red line being a 60 month running mean.

Figure 2. As in Figure 1 but for the third rotated EOF.

Figure 3. As in Figure 1 but the SST and surface flux anomalies are those simulated by the ocean GCM-AML model

Figure 4. As in Figure 2 but the SST and surface flux anomalies are those simulated by the ocean GCM-AML model

Figure 5. Latitude-time plot of zonally averaged anomalies of NCEP SST. The time series at each point have been filtered with two passes of a 36 month running mean to remove variability with periods less than eight years.

Figure 6. Latitude-time plots of (a) zonally averaged anomalies of SST, (b) latent plus sensible surface heat flux and (c) ocean heat transport from the ocean GCM-AML model. The model results have been time filtered as in Figure 5.

Figure 7. Latitude-time plots of four terms contributing to the ocean heat transport of the ocean GCM-AML model, (a) $\rho c_p H \bar{v} T'_y$, (b) $\rho c_p H v' \bar{T}_y$, (c) $\rho c_p H \bar{w} T'_z$ and (d) $\rho c_p H w' \bar{T}_z$. Time filtering has been applied.

Figure 8. The second rotated EOF of NCEP surface wind anomalies together with associated anomalies in SSTs and ocean heat transport as produced by the ocean GCM-AML model. SSTs are colored and the ocean heat transport anomalies are contoured with a contour interval of $1Wm^{-2}$. Ocean heat transports are defined positive if they warm the ocean.

Figure 9. As in Figure 8 but for the third rotated EOF of the NCEP surface winds.

Figure 10. As in Figure 6 but for the case of the mean ocean circulation model coupled to the AML model.

Figure 11. As in Figure 6 but for the case of the ocean mixed layer model coupled to the AML model.