Internal Variability of the Tropical Atlantic Ocean

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A 100 year integration of an eddy resolving numerical model of the tropical Atlantic is analyzed to quantify the interannual variability caused by internal variability of ocean dynamics. It is found that, except for the spring position of the SST maximum, the strength of internal variability in the tropical Atlantic is comparable to published mid-latitude values but is dwarfed by the strength of the seasonal cycle. During spring however, the equatorial meridional SST gradient is very weak, and internal oceanic variability causes a variability in the position of the SST maximum that is comparable to its observed variability. It is shown that these variations in the SST are due to tropical instability waves whose strength varies from year to year, even under climatological forcing. The results suggests that in winter, the predictability of the location of the tropical SST maximum is limited to the persistence time of SST anomalies which is approximately 100 days.

1. INTRODUCTION

The coupled ocean-atmosphere system varies on many timescales; however, it is the variability on multi-year and decadal timescales that currently receives the most attention. Understanding these long term variabilities will improve climate forecasts and the interpretation of historical climate records. Variability in the ocean-atmosphere system can be attributed to external forcing (e.g. ice ages), ocean-atmosphere coupling (e.g. El Niño), internal atmospheric variability (e.g. North Atlantic Oscillation) and, the focus of the present study, internal oceanic variability (e.g. Kuroshio path). Because of the relatively low ocean temperature in higher latitudes, ocean-atmosphere coupling is thought to be stronger in the tropics, whereas the relatively low tropical ratio between background velocity and planetary wave speed suggests that the tropical oceans are governed by linear dynamics, thereby restricting internal variability to higher latitudes. Observational evidence for internal oceanic variability in mid-latitudes has been reported by *Taft* [1972] who shows that the Kuroshio switches back and for between a large and a small meander state. Both states can persist for several years and the transitions between them occur within a couple of months [*Kawabe*, 1986]. Observations of the Gulf Stream also show a weak bimodality of the path [*Bane and Dewar*, 1988]. High resolution ocean general circulation models (OGCMs) are able to reproduce the observed bimodalities [*Schmeits and Dijkstra*, 2001].

Several authors demonstrated that the observed internal variability of the western boundary currents can be understood within the framework of dynamical systems theory [*Jiang et al.*, 1995, *Primeau*, 1998, *Meacham*, 2000, *Simmonet et al.*, 2003, and references therein]. These studies typically use a one or two layer high resolution OGCM set in a rectangular basin with a mid-latitude double gyre. For certain ranges of Rossby and Ekman numbers the solutions exhibit chaotic or limit cycle behaviour which is usually tied

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to the strength of the inertial recirculation gyres near the western boundary. The not very comforting picture that emerges from these studies is that the nature of the ocean circulation could be sensitive to parameters that are not well known (e.g. friction or boundary conditions). The present authors are not aware of a study that shows this internal mid-latitude varibility to have an impact on large scale climate, but it can be speculated that it affects the water mass properties and the heat budget of the mid-latitude oceans.

In the tropical Atlantic, there is a large interannual variability of the seasonal march of the Inter-Tropical Convergence Zone (ITCZ, *Chiang et al.*, 2002] with disastrous consequences for the Brazilian and West African population.Although the mechanisms behind this variability are not entirely clear [*Xie and Carton*, 2004], internal oceanic variability has to our knowledge not yet been suggested. There are no reports of internal interannual variability in the tropical oceans; in fact, it would be difficult to observe considering the strength of El Niño and the seasonal cycle in the tropics. Furthermore, the success of *Cane et al.* [1986] in predicting El Niño suggested that "the tropical ocean response on interannual timescales is reasonably well captured by linear or weakly nonlinear approximations to the ocean dynamics" [*Neelin et al.*, 1998]. However, we, the authors, recently concluded several studies that show that at least in the Atlantic nonlinear dynamics are a major part of the tropical circulation: the barotropically unstable North Equatorial CounterCurrent (NECC) generates rings which carry South Atlantic water and potential vorticity into the subtropical gyre [*Jochum and Malanotte-Rizzoli*, 2003a] and the unstable Equatorial UnderCurrent - South Equatorial Current (EUC-SEC) system generates tropical instability waves (TIWs; *Jochum et al.*, 2004; JMB hereafter) that drive the Atlantic Tsuchiya jets [*Jochum and Malanotte-Rizzoli*, 2003b]. TIWs have a period of approximately 20 to 40 days and, due to their nonlinear nature, are of varying strength every year, even under seasonal forcing (JMB). Since they are a major contributer to the equatorial mixed layer heat and momentum budget [*Hansen and Paul*, 1984] one can infer that the equatorial temperature and velocity fields change from year to year. The present study quantifies, with the help of an OGCM, to what extent the nonlinear effects in the tropical Atlantic ocean contribute to its observed interannual variablity. It is not attempted, like in the aforementioned mid-latitude studies, to determine the particular kind of nonlinear regime that dominates the tropical Atlantic. The OGCM used here has in comparison to JMB a more realistic oceanic and atmospheric mixed layer model and is numerically more efficient, so that high resolution runs lasting 100 years are feasible.

Van der Vaart and Dijkstra [1998] showed that inidealized coupled tropical ocean-atmosphere models intraseasonal instabilities in conjunction with seasonal forcing can lead to interannual variability. Whether instabilities can generate interannual variability without atmospheric coupling is investigated here. One important difference between the tropical Atlantic and the aforementioned idealized mid-latitude studies is the fate of the eddy kinetic energy (EKE). In the latter, the EKE is focused on a small region along the western boundary by two converging western boundary currents and the westward group speed of Rossby waves; on the other hand, in the tropical Atlantic the orientation of the Brazilian coastline allows the North Brazil Current rings to carry away the EKE generated by the NECC from the equatorial Atlantic into the Caribbean Sea. TIWs, the other large carrier of EKE, are mostly dissipated before they canreach the western boundary (JMB). Thus, instead of the basin wide growth and collapse ofrecirculation gyres which can be observed in idealized mid-latitude studies, the internal variability in the tropical Atlantic is likely to produce more subtle changes due to local instability processes. Nevertheless, the present study shows that these instabilities can contribute a significant portion to the observed interannual variability of the location of the SST maximum.

The following section describes the numerical model, Section 3 describes and quantifies the internal interannual variability and discusses mechanisms for this variability. Section 4 summarizes the results.

2. MODEL DESCRIPTION

The OGCM employed for this study is the reduced gravity, primitive equation, sigma-coordinate model of *Gent and Cane* [1989]. The OGCM is coupled to an advective atmospheric mixed layer model which computes surface heat fluxes without any restoring boundary conditions or feedbacks to observations [*Seager et al.*, 1995; *Murtugudde et al.*, 1996]. A variable depth oceanic mixed layer represents the three main processes of oceanic turbulent mixing, namely, the entrainment/ detrainment due to wind and buoyancy forcing, the gradient Richardson number mixing generated by the shear flow instability, and the convective mixing related to static instabilities in the water column [*Chen et al.*, 1994].

In previous studies this model has demonstrated its ability to reproduce the observed SST and circulation in the tropical Atlantic [*Murtugudde et al.*, 1996 and *Inui et al.*, 2002]. In this study, the model is initialized with *Levitus* [1994] temperature and salinity fields, driven by seasonal *Hellerman and Rosenstein* [1983] winds, has a $\frac{1}{4}$ degree horizontal resolution and 8 layers in the vertical. At the meridional boundaries at 25°S and 25°N, temperature and salinity are restored to *Levitus* [1994]. The model is spun up for 20 years and the presented results are taken from the subsequent 100 years of simulation. Years 21 and 22 of the data are saved as 5 day snapshots to compute the strength of the eddy field whereas the remainder is saved as monthly means to limit the amount of data to a managable size. Most of the analysis is done with anomaly fields for which the seasonal cycle has been removed. The correlation analysis was performed after smoothing the anomalies with an 11 month Hanning smoother [Press et al., 1992] so that only the integral effects of the high frequency oscillations remain. It should be pointed out that the separation between mean, seasonal, intra-, and interannual variability is mainly mathematical. Because TIWs are nonlinear, they will contribute not only to intraseasonal variability but also to the mean, the seasonal cycle and, as shown here, to interannual variability. Thus, the seasonal cycle is the result of seasonal changes in the direct surface forcing and the forcing due to seasonally varying instabilities.

The pattern and strength of the variability is, apart from the southward shift of the NBC/NECC retroflection, consistent with altimeter observations [*Stammer*, 1997; Figure 1].

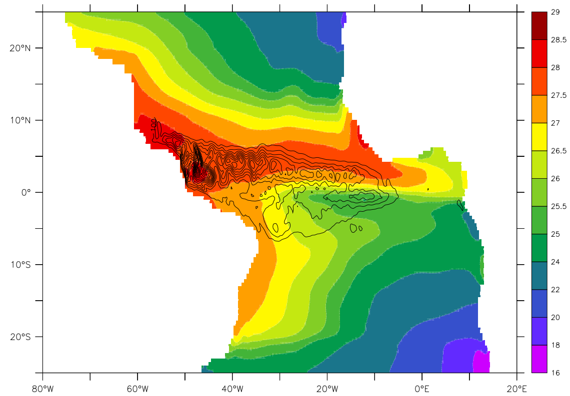

Figure 1. Annual mean of the SST, superimposed is the variance of the meridional velocity in the mixed layer (contour lines: $100 cm^2/s^2$, the maximum is $1800 cm^2/s^2$). The seasonal cycle has been removed from the velocity before computing the variance.

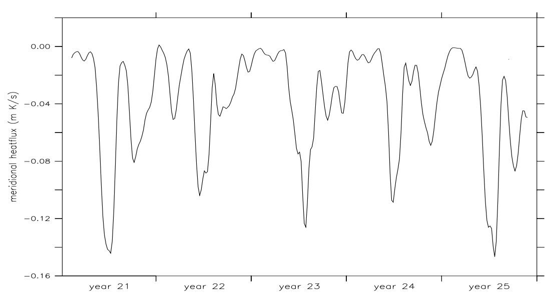

Figure 2. Meridional heatflux on the equator at the surface at 20^oW. Note the difference in strength from year to year.

The southward shift of the retroflection can be explained by the model's weak meridional overturning circulation of 2 Sv [*Fratantoni et al.*, 2000; *Jochum and Malanotte-Rizzoli*, 2001]. Accordingly, the simulated EKE along the Brazilian coast at 4^oN and 8^oN is about 40 % weaker than observed [*Johns et al.*, 1990, 1998], whereas the simulated EKE for the TIWs and for the NBC at the equator matches the observed values [*Weisberg and Weingartner*, 1988 and *Schott et al.*, 1993, respectively].

As motivated in the introduction, internal variability of the SST is most likely to arise in regions with strong instability processes. Figures 1 and 2 suggest that for the present study the most interesting region is the central basin along the equator, where high eddy activity is combined with a strong meridional temperature gradient. The next section will describe and quantify the internal variability in this experiment.

3. INTERNAL VARIABILITY

An energy analysis connects this study with the aforementioned idealized mid-latitude studies:

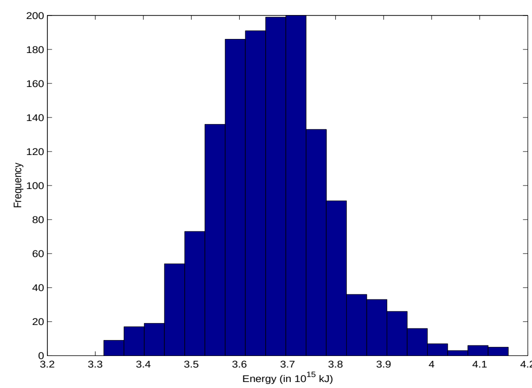

Figure 3. Number of occurences of different energy states after removal of the seasonal cycle. For example, there are 200 months in which the energy is between 3.70 and $3.75 \cdot 10^{15}$ kJ.

near the equator, variations of the kinetic energy are an order of magnitude larger than variations in the potential energy [*Pedlosky*, 1979, *Weisberg and Weingartner*, 1988], therefore only kinetic energy is considered here, specifically the kinetic energy integrated over all model layers of the most energetic part of the tropics (10^oS to 15^oN). The solution's energy levels (after removing the seasonal cycle) are narrowly distributed around a mean and are slightly skewed towards states of higher energy (Figure 3). This is different from the results of the idealized mid-latitude experiment of *McCalpin and Haidvogel* [1996] who find two distinct peaks in their energy distribution, a low level and a high level state which correspond to two different states of the circulation. In an experiment similar to *McCalpin and Haidvogel* [1996], *Meacham* [2000] shows that a low viscosity simulation can develop strong aperiodic oscillations which destroy the limit cycle behaviour observed by *McCalpin and Haidvogel* [1996]. The energy distribution of the present simulation is similar to the low viscosity case in *Meacham* [2000]: There are no multiple prefered states of the circulation, but the irregular TIW activity (Figure 2) causes a spread of energy around the mean. Apart from the annual harmonics, there is no spectral peak in the energy time series and, as in the altimeter observations by *Stammer* [1997], the spectrum is white on timescales longer than 100 days (not shown). Since the seasonal cycle of the tropics is considerably larger than that at mid-latitudes, the contribution of the internal variability to the energetics of the tropics tends to be small despite the internal variability in the tropics being comparable to that in the mid-latitudes.

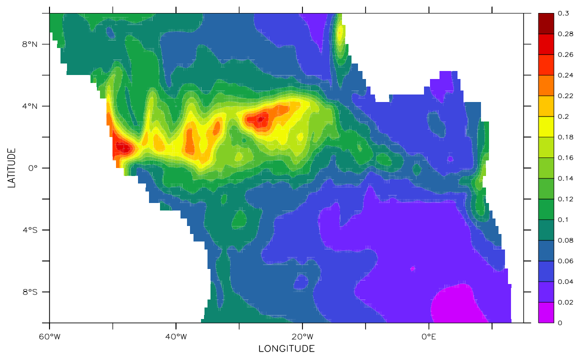

Figure 4. Ratio between the standard deviation of the internal SST anomalies and the standard deviation of the seasonal cycle.

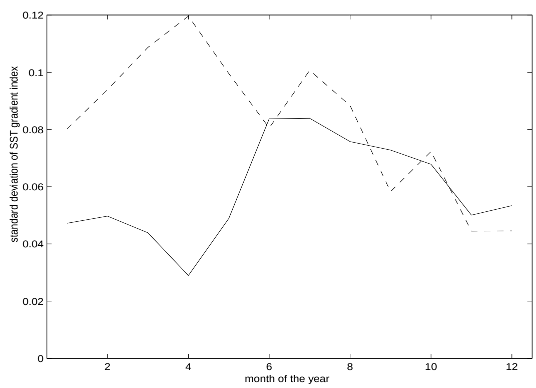

Figure 5. The seasonal cycle of the standard deviation of the SST gradient index for the observations (dashed line) and the model (solid line). The index is here computed as the difference between the zonally averaged (35^oW to 15^oW) SST between the equator and 1^oN and the equator and 1^oS.

Although the internal variability in the kinetic energy is negligible in the tropical Atlantic ocean, it is not obviously so for the SST. The model's internal interannual SST variability rarely exceeds 0.2 K anywhere, but there are areas where this signal can be as strong as 30% ofthe seasonal signal of the SST (Figure 4). Two different SST indicies are thought to be important for the tropical Atlantic: the Atlantic Niño and the Atlantic Gradient [*Servain*, 1991; *Zebiak*, 1993] The first index uses the SST anomalies averaged over an equatorial domain (here and in *Zebiak* [1993]: 3^oS to 3^oN and 20^oW to 0^oW) to determine the presence of an Atlantic coupled mode similar to the Pacific ENSO: the Atlantic Niño. The *Reynolds and Smith* climatology [1994, RS from here on] and results from a numerical model driven by NCEP reanalysis winds [J. Kroeger, manuscript in preparation, 2004] show that, after removing the seasonal cycle, the Atlantic Niño index has a standard deviation (*std*) of 0.5 which is approximately ten times larger than the internal variability produced in the model (not shown). Hence, internal variability in the tropical Atlantic ocean is unlikely to have a significant impact on the Atlantic Niño.

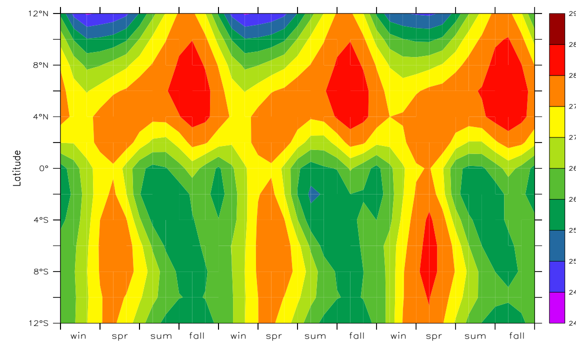

Figure 6. 3 years of SST averaged from 35^oW to 15^oW. Note the strong SST gradient around the SST maximum at 6^oN during summer and the weak gradient during spring, especially the reversal of the SST gradient in the third spring.

The situation is very different for the gradient index which defines a meridional SST gradient. Near the equator the wind is directed from low to high SST, therefore the position of the ITCZ is connected to the position of the SST maximum [*Lindzen and Nigam*, 1987; *Ruiz-Barradas et al.*, 2000]. The interannual variability of the ITCZ position manifests itself primarily as a meridional displacement from its mean position and leads to severe rainfall anomalies in West Africa and Northeast Brazil [*Nobre and Shukla*, 1996]. Thus, a small change in the seasonal cycle of the SST maximum can have a large impact on the climate ofthese areas.

In the present study, the internal variability in the model can account for a signifcant part of the observed interannual variability in the SST gradient in a narrow band centered on the equator (Figure 5). Basing the index on areas further polewards will reduce the relative contribution of the internal variability; for example, if instead of the area between 1^oS and 1^oN we choose thearea between 5^oS and 5^oN the simulated internal variability is only about 50% of the observed interannual variability in the summer and 15% in the spring. For the area between 20^oS and 20^oN the values are 10% and 4%, respectively. The seasonal cycle of the internal variability reflects the seasonality of the TIWs: weak in the early spring, sudden increase in May, and slow decay during fall and winter.

Even though the relative contribution of the internal variability to the interannual variability is largest in the summer and fall, the position of the SST maximum is most sensitive to disturbances in spring (April to June) when the SST gradient is weak (Figure 6). In spring the insolation maximum returns from the southern hemisphere and crosses the equator. During the austral summer the waters south of the equator are heated, the cold tongue vanishes and the meridional temperature gradient is very weak [*Mitchell and Wallace*, 1992]. Due to this weak gradient, small disturbances caused by internal variability are sufficent to cause the spring maximum in the present study to be sometimes north and sometimes south of the equator which leads to a large *std* of the yearly southernmost position of the SST maximum of 3.5^o (mean: 3.3^oS). Based on the RS climatology the observational value is: 2.0^oS $\pm 3.2^o$. During the boreal summer the contributions of the internal variability to the position of the SST maximum are negligible because of the strong meridional temperature gradient: The *std* of the northernmost latitude of the SST maximum is 0.2^o as opposed to the observed 2.3^o. We conclude that, although internal variability in the tropical Atlantic is largely neglible because of the strong seasonal cycle in the tropics, it causes a significant variability in the position of the SST maximum during spring and therefore must be accounted for in studies of tropical climate variability. The question now is whether this SST variability is generated locally, or remotely and subsequently advected to the surface.

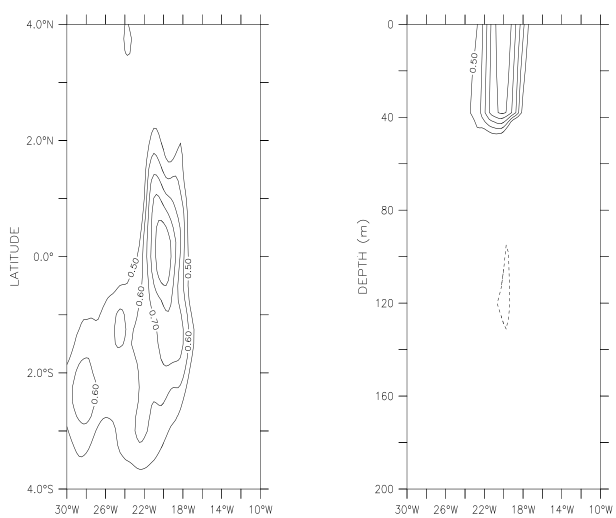

Figure 7. Correlation of the SST anomalies at 20^oW/0^oN with the surrounding SST anomalies (left) and with the temperature anomalies at 0^oN (right). Only correlations with absolute values of 0.5 or higher are shown.

The internal SST variability is limited to the equatorial band which suggests that it is either generated locally by TIWs or advected by the EUC and upwelled into the mixed layer. A correlation analysis rules out the advection hypothesis and supports the TIW hypothesis: The SST anomaly at the equator at 20^oW is correlated with the temperature anomaly in the rest of the domain. This particular point is chosen because it has both, strong TIW activity and upwelling. Since water in the EUC travels about 2000 km in a month, the analysis should yield positive values to the west of 20^oW and below the surface if the anomalies were advected. This is clearly not the case (Figure 7, right); instead the correlation pattern reflects the typical structure of TIWs: high meridional coherence and anticorrelation between surface and thermocline (JMB, Figure 7, left).

4. SUMMARY AND DISCUSSION

A high resolution OGCM with climatological forcing has been used to study the internal variability of the tropical Atlantic. It is found that because of the strong seasonal cycle (and not because of the absence of nonlinear effects) the contribution of internal variability to the interannual variability of the kinetic energy is mostly negligible. However, near the equator internal variability can modulate the seasonal cycle of SST from year to year and causes interannualvariability. Most importantly it can change the position of the spring position of the SST maximum, whose internal variability in the model is comparable to its observed interannual variability. The main sources of internal variability in the tropical Atlantic are the NECC and EUC. Their instabilities generate high frequency waves that have interannual variations in strength. In the case of the EUC, the instabilities are in a region with a strong meridional temperature gradient which leads to interannual SST variabilities. Thus, nonlinear and aperiodic TIW generation leads to a significant variance of the spring time position of the SST maximum: It can be north as well as south of the equator. This has important implications for the predictability of tropical Atlantic climate, because it means that the spring time position of the SST maximum *cannot* be known before the preceding winter, limiting the forecast range to the persistence time of temperature anomalies of the equatorial mixed-layer which is approximately 100 days [*Kessler et al.*, 1996; see also *Saravannan and Ping*, 2004, for a discussion on predictability]. The importance of accurate TIW representation might also explain the problems that coupled models have in reproducing eastern tropical Atlantic climate [*Davey et al.*, 2000].

The seasonal cycle of the ITCZ is observed to be very uncertain in the spring. Similar to the modeled SST maximum its spring time position can be north or south of the equator [*Chiang et al.*, 2002]. While theory and observations suggest that the ITCZ position depends on the position of the SST maximum, it is not clear how strong the internal variability influences the ITCZ position. *Hashizume et al.* [2001] provide observational evidence for the Atlantic and Pacific that the TIWs directly affect the local wind field. However, how much the internal SST variability will perturb the seasonal cycle of the ITCZ position has to be investigated with an OGCM that is coupled to an atmospheric GCM which will be part of our future research.

Since the TIWs are an important part of the equatorial heat budget (JMB) and are shown here to have the potential to perturb the seasonal cycle of the ITCZ during spring, it is worthwhile asking to what extent they provide a positive or negative feedback for anomalies in the cross equatorial temperature gradient. *Chang et al.* [1997] propose a coupled ocean-atmosphere mode for the Atlantic in which anomalies in the cross equatorial wind lead to anomalies in the cross equatorial temperature gradient which amplify again the initial wind anomalies. The TIW heat flux depends on the meridional temperature gradient [*Hansen and Paul*, 1984], therefore an increased northward temperature gradient would lead to an increased southward heat flux, resulting in a negative feedback. Furthermore, *Philander and Delecluse* [1983] showed that an increased northward wind across the equator leads to a strengthening of the EUC which should lead to a stronger TIW activity and an increased southward heat flux, again a negative feedback. There is observational evidence for this: Compared to 1983, 1984 has a weaker meridional SST gradient (RS) *and* weaker TIWs [*Weisberg and Weingartner*, 1988; their Figure 7]. This suggests that the positive feedback cycle of *Chang et al.* [1997] could be damped by TIWs. Numerical studies are currently under way to support this proposed negative TIW feedback.

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