Tellus (2006), 58A, 307–319
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Understanding the predictability of seasonal precipitation over northeast Brazil

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(Manuscript received 31 March 2005; in final form 4 November 2005)

ABSTRACT

Using multiple long-term simulations of the Center for Ocean–Land–Atmosphere Studies (COLA) atmospheric general circulation model (AGCM) forced with observed sea surface temperature (SST), it is shown that the model has high skill in simulating the February–March-April (FMA) rainy season over northeast Brazil (Nordeste). Separate sensitivity experiments conducted with the same model that entails suppression of all variability except for the climatological annual cycle in SST over the Pacific and Atlantic Oceans reveal that this skill over Nordeste is sensitive to SST anomalies in the tropical Atlantic Ocean. However, the spatial pattern of SST anomalies in the tropical Atlantic Ocean that correlate with FMA Nordeste rainfall are in fact a manifestation of El Niño Southern Oscillation (ENSO) phenomenon in the Pacific Ocean.

This study also analyzes the failure of the COLA AGCM in capturing the correct FMA precipitation anomalies over Nordeste in several years of the simulation. It is found that this failure occurs when the SST anomalies over the northern tropical Atlantic Ocean are large and not significantly correlated with contemporaneous SST anomalies over the eastern Pacific Ocean. In two of the relatively large ENSO years when the model failed to capture the correct signal of the interannual variability of precipitation over Nordeste, it was found that the meridional gradient of SST anomalies over the tropical Atlantic Ocean was inconsistent with the canonical development of ENSO. The analysis of the probabilistic skill of the model revealed that it has more skill in predicting flood years than drought. Furthermore, the model has no skill in predicting normal seasons. These model features are consistent with the model systematic errors.

1. Introduction

Nordeste in northeast Brazil (NOR in Fig. 1) has been a very promising area in the tropics for verifiable seasonal climate forecasts produced from numerical climate models (Goddard et al., 2003; Folland et al., 2001; Sun et al., 2005). It is also a region that is prone to droughts periodically from global teleconnections (Hastenrath and Heller, 1977). Therefore, understanding the predictability of seasonal precipitation varability in the rainy season over Nordeste, which supports a vast agrarian society, is of great societal relevance. Empirical models for predicting precipitation over Nordeste at seasonal time scales have also shown tremendous promise (Hastenrath and Greischar, 1993; Greischar and Hastenrath, 2000; Moura and Hastenrath, 2004). However, in this study we will examine the predictability of the seasonal (February–March–April) precipitation over Nordeste from the Center for Ocean–Land–Atmosphere Studies (COLA) atmospheric general circulation model (AGCM) that displays relatively high degree of skill (Misra, 2004). The objective of this study is to understand the sources of this precipitation predictability in the AGCM.

Although precipitation over Nordeste follows a simple linear relationship with Niño SST anomalies (SSTA), Giannini et al. (2001) and Saravanan and Chang (2000; hereafter SC2000) found from their modeling studies that a large proportion of this variability is forced from the tropical Atlantic SSTA. This is also supported from observations (Hastenrath and Greischar, 1993; Nobre and Shukla, 1996). However, there is also strong evidence both from observations (Nobre and Shukla, 1996; Curtis and Hastenrath, 1995; Enfield and Mayer, 1997) and modeling studies (SC2000), which show that the Atlantic SST variability is strongly influenced by El Niño Southern Oscillation (ENSO). This relationship between ENSO and northern tropical Atlantic SSTA has a lag of about one season. Enfield and Mayer (1997) showed that the ENSO manifests over northern tropical Atlantic Ocean with a delay of about 2–4 months which is associated with the mixed layer response to surface heat fluxes. In this study the atmospheric modeling experiments are conducted with prescribed SST, and therefore, it precludes any discussion of the causes of Atlantic SST variability.

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DOI: 10.1111/j.1600-0870.2006.00175.x

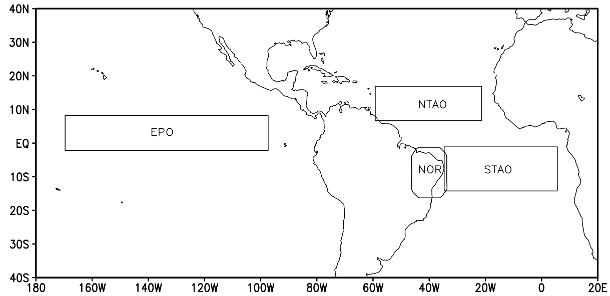

Fig. 1. The outline of Nordeste area in northeast Brazil is shown. The outline of areas denoting EPO (Eastern Pacific Ocean), NTAO (North Tropical Atlantic Ocean), STAO (South Tropical Atlantic Ocean) is also shown. The outline of these oceanic areas is derived from a discussion in Section 4.2.

The purpose of this study is to ascertain the cause of the precipitation variability over Nordeste and its sensitivity to boundary forcing. Furthermore, this study will also investigate the probabilistic skill of the model over Nordeste. Inherently, the seasonal climate is probabilistic in nature (Barnston et al., 2005). This is because any given observed seasonal anomaly convolves the boundary forced signal with the atmosphere's internal variability that is not boundary forced and is considerd noise. Brankovic and Palmer (1997) assert that the slowly varying boundary forcing affect the whole atmospheric climate attractor rather than a single phase-space trajectory. Kirtman (2003) provides compelling evidence that probabilistic skill assessment of climate forecasts are complimentary to deterministic evaluation of model forecasts.

The domain of Nordeste outlined in Fig. 1 extends both into northern and southern Nordeste. These two regions have slightly different annual cycle and variability (Nobre and Shukla, 1996). It is observed that the rainy season in northern (southern) Nordeste is in January–February–March (March–April–May) and its variability is strongly associated with the ITCZ (South Atlantic Convergence Zone; SACZ) in the Atlantic Ocean. However, it is to be noted that at the horizontal resolution of most of the current AGCMs (typically around 250 km resolution), this subtle distinction is barely resolved. Furthermore, choosing a domain size much smaller than what is shown in Fig. 1 will grossly under-sample the model features in the domain relative to its horizontal resolution. In a significant development, the VIth International Workshop on Climate Prediction (and evaluation) for Nordeste organized by the State of Ceara's Foundation for Meteorology and Water Resources departed from the tradition of providing forecast for the season of January–February–March to February–March–April to facilitate the evaluation of the delayed response of Nordeste precipitation to ENSO (A.D. Moura, 2004, personal communication; Sun et al., 2005).

In the following section, we will briefly outline the COLA AGCM followed by a description of the experiments. The results are discussed in Section 3 and summary and concluding remarks are made in Section 4.

2. Model description

The AGCM used in this study is version 2.2 of the Center for Ocean–Land–Atmosphere Studies (COLA) global spectral model at T42 (2.5°) horizontal resolution and 18 levels (COLA AGCM). This version of the model uses the dynamical core of the National Center for Atmospheric Research Climate Community Model version 3 (CCM3) described in Kiehl et al. (1998). The dependent variables of the model are spectrally treated except the moisture variable which is advected using the semi-Lagrangian technique. The parameterization of deep convection follows the relaxed Arakawa-Schubert scheme (Moorthi and Suarez, 1992). The parameterization of shallow convection follows Tiedtke (1984). The subgrid scale exchange of heat, momentum and moisture is accomplished via a turbulent closure scheme, level 2.0 (Mellor and Yamada, 1982). The diagnostic cloud fraction and optical properties are similar to CCM3 (Kiehl et al., 1998) and are described in DeWitt and Schneider (1997). The terrestrial and short-wave radiation follows Harshvardhan et al. (1987) and Davies (1982), respectively. A fourth order horizontal diffusion is applied to all variables except the moisture variable. A mean surface orography (Fennessy et al., 1994) is used to represent surface elevation. Dry convective adjustment and gravity wave drag are not invoked in the model integrations. The atmospheric model is coupled to the Simplified Simple Biosphere model (SSiB) documented in Xue et al. (1991, 1996).

3. Design of experiments

Misra (2004) showed that compared to the rest of the tropical and subtropical South America, rainfall predictability over Nordeste was slightly higher in the multi-year simulations compared to seasonal simulations. In other words, the climate drift of the COLA AGCM over this region of South America was relatively small and the influence of the slowly varying observed boundary conditions was comparatively large. The intent of the proposed design of model experiments is to understand this influence of the surface boundary condition on the precipitation over Nordeste in their rainy season from multi-year COLA AGCM integrations.

For this study, we ran six ensemble members of the control COLA AGCM (hereafter control) for 19 yr starting from 0000 UTC, 15 December 1978. The atmospheric initial conditions for these ensemble members were generated by initially running the COLA AGCM from NCEP reanalysis for 0000 UTC, 15 December 1978 for a week and resetting the date on the restart file to the initial date. This procedure was repeated five more times to obtain synoptically independent atmospheric initial conditions for the other ensemble members. This procedure has been adopted in the past (Misra, 2003; Kirtman et al., 2001). The surface boundary condition of SST is obtained from the monthly mean of Hadley center sea ice and sea surface temperature (HADISST) data set (Parker et al., 1999). This data set is available on a $1^\circ \times 1^\circ$ grid from 1870 to present. The soil

Table 1. The summary of the experiments conducted in the study

Name	SST	Integration period	Ensemble size
Control	HADISST	1979–1997	6
PAC	Climatological SST over the Pacific Ocean and HADISST in other ocean basins	1979–1997	6
ATL	Climatological SST over the Atlantic Ocean and HADISST in other ocean basins	1979–1997	6

moisture fields are obtained from a 2-yr climatology of the global soil wetness project (Dirmeyer and Zeng, 1999).

Additionally, two sets of six ensemble member experimental model runs were conducted using the same initial atmospheric and land surface conditions as in the control COLA AGCM. However, in one of these sets comprising of six experimental runs seasonally varying climatological SST was used over the entire Pacific Ocean while in the rest of the ocean basins the observed SST was used (herefafter PAC). Similarly, in the other set of six experimental runs, the Atlantic SST variability at all scales was suppressed except for the climatologically varying annual cycle (herefafter ATL). The purpose of these experiments is to assess the influence of remote and local SST variations on the rainfall variability in the rainy season of Nordeste. In Table 1 we have summarized the details of the conducted experiments.

4. Results

In discussing the results of this study we shall be extensively using the climate prediction center merged analysis precipitation (CMAP) data set (Xie and Arkin, 1996) made available on a 2.5° × 2.5° latitude–longitude grid to verify and compare the model simulations. The verification is made over a time period from 1979 to 1999. Furthermore, unless specified we shall be depicting the results from the ensemble mean (averaged over the six ensemble members) of the model runs. In the subsequent sections, we shall first validate the annual cycle of precipitation over Nordeste from the control run to understand if the seasonal cycle is captured reasonably well. This will be followed by a discussion on interannual variability of the large-scale circulation field and the diagnosis of the teleconnection patterns of Nordeste rainfall with global distribution of SSTA in the control run. These teleconnection patterns typify the influence of SSTA on regional precipitation patterns (Horel and Wallace, 1981). Then a discussion of the results from a similar construction of teleconnection patterns from the sensitivity runs (PAC and ATL) will follow in Section 4.3. This discussion will highlight the contribution of the SST variability of the Pacific and the Atlantic Oceans separately on the predictability of Nordeste precipitation in the control run. In Section 4.4 we will examine the probabilistic skill of the control run in an attempt to include the unforced chaotic variability on the predictability of Nordeste precipitation.

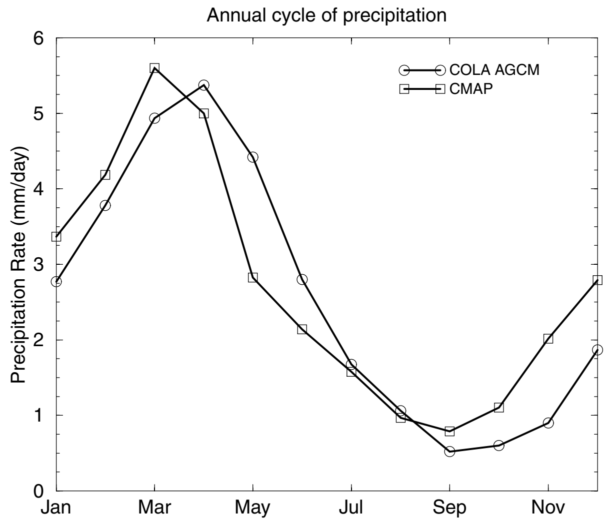

Fig. 2. The annual cycle of precipitation over Nordeste in mm day^{-1}.

4.1. Annual cycle

The mean annual cycle of precipitation over Nordeste averaged from 1979 to 1999 is shown from the control run and CMAP observations in Fig. 2. In the CMAP data set, it is clear that February–March–April (FMA) comprises the wet season of Nordeste. The control run does a reasonable job in picking this annual cycle of precipitation over Nordeste despite the dry (wet) bias from September through March (April through August). This bias in the COLA AGCM makes the March–April–May season wettest over Nordeste. In Fig. 3, we have plotted the correlations of the interannual variations of the monthly mean precipitation anomalies over Nordeste from the control run with the corresponding CMAP observations for the 19-yr model integration period (1979–1997). It is seen from this figure that in the months of February, March and April, the model has the highest skill compared to all other months except in July and August when the rainfall is transitioning to the dry season. Therefore, despite the prevalent bias of excessive climatological precipitation in April over Nordeste, it is worthwhile to examine the factors that determine the variability of FMA seasonal precipitation over the region in the COLA AGCM.

4.2. Interannual variability

The fact that the ensemble mean of a set of COLA AGCM integrations can reproduce the precipitation variability over Nordeste with a relatively high skill obviously points to a strong external forcing. One obvious candidate of such an external forcing is

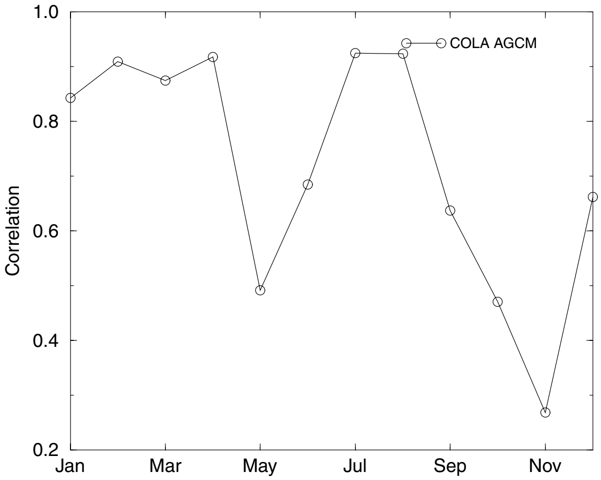

Fig. 3. The correlation of monthly anomalies of precipitation over Nordeste from the control COLA AGCM run with CMAP observations.

the slowly varying surface boundary condition of SST. In Fig. 4, we show the anomalous divergent wind circulation and velocity potential at 200 hPa for the FMA season from the control run and the correpsonding NCEP reanalysis. In this figure, the climatology is computed over the 19-yr period of the model integration and the warm (cold) ENSO years are taken to be 1983, 1987 and 1992 (1985, 1989 and 1996). Although the SSTA in the warm and cold ENSO episodes are not symmetric and nor is the atmospheric response to it symmetric (Hoerling et al., 2001), this figure shows that COLA AGCM is able to reasonably simulate the eastward (westward) shift of the Walker circulation in response to the prescribed SSTA. This anomalous circulation in the COLA AGCM is, however, weaker than the corresponding NCEP reanalysis. Thus besides reproducing the precipitation variability over Nordeste reasonably well (Misra, 2004), the large-scale variability of the equatorial circulation in response to the SSTA in the COLA AGCM is also verifiable. This adds further confidence and motivation in understanding the source and cause of the anomalous rainfall predictability over the Nordeste region from the COLA AGCM.

In Fig. 5, we have plotted the teleconnection patterns obtained from correlating FMA seasonal precipitation over Nordeste from CMAP (Fig. 5a) and control run (Fig. 5b) with contemporaneous global SSTA. It is apparent from the figure that the COLA AGCM does a reasonable job in simulating the observed teleconnection pattern over the western and eastern tropical Pacific Oceans. There is, however, an erroneously significant correlations over the stratus region of south eastern Pacific Ocean in the control run. The model has a problem in simulating the stratus clouds over cold waters (not shown) and this erro-neous correlation and its possible influence on Nordeste rainfall variability may be a reflection of this problem. Similarly, the teleconnection over southern tropical Atlantic Ocean is well depicted by the control run. The model, however, is unable to pick the correlations to the southeast of Indonesia. Furthermore, the model simulates a rather strong correlation over the northern tropical Atlantic Ocean (unsupported from the observed teleconnection patterns in Fig. 5a) that is comparable to that over the eastern Pacific Ocean. The dipole-like correlation structure over the tropical Atlantic Ocean (with negative correlations in the north tropical Atlantic and positive correlations in the south tropical Atlantic) obtained from the control run (Fig. 5b) is similar to that obtained in SC2000. In the modeling study of SC2000, they found that ENSO contributes to this dipole structure in the covariance between the tropical Atlantic SST and rainfall in the Nordeste region; in the absence of ENSO signal the correlations lose its dipole-like structure and are dominated by SST variability in the south tropical Atlantic. Furthermore, they showed that when Niño3 index is regressed against the tropical Atlantic SST, a dipole-like structure similar to that seen in Fig. 5b is observed. In Fig. 6a we have shown the observed equatorial FMA SSTA over the Pacific Ocean for the simulation period (1979–1997). If we remove the years of the four largest SSTA over Niño3 which correspond to the years of 1983, 1985, 1989 and 1992 and recompute the teleconnection pattern with the precipitation over Nordeste from the control run as in Fig. 5b, then we obtain the teleconnection pattern shown in Fig. 5b. This teleconnection pattern (in Fig. 6b) is bereft of the dipole-like correlation seen earlier in Fig. 5b. Therefore, this corroborates the results of SC2000 that the ENSO manifestation of SSTA over tropical Atlantic forces a part of the interannual variability of precipitation over Nordeste. However, the absence of this dipole correlation structure when using the observed precipitation variability (in Fig. 5a) suggests that the model response to ENSO forcing over Nordeste is stronger than observed.

In the observational studies of Chiang et al. (2002), it is suggested that the direct influence of Pacific SSTA mediated through anomalous Walker circulation has also an important bearing on the variability of the ITCZ in the Atlantic Ocean. This atmospheric teleconnection bridge would, however, warrant a lead/lag relationship between Pacific SSTA and Nordeste rainfall for at least two reasons: one, ENSO variability is phase locked to its seasonal cycle that peaks a season or two earlier to the Nordeste rainy season; two, the delay associated with the tropical Atlantic Ocean response to the modulation of the surface fluxes by the atmospheric teleconnection bridge. In Fig. 7 similar to Fig. 5, we have plotted the correlation of the FMA seasonal precipitation over Nordeste from observations and the control COLA AGCM integration with the leading November–December–January (NDJ) global SSTA. It is seen from this figure that the correlation patterns in both the observations and the model are similar to each other and to that in Fig. 5. However, the dipole structure seen in Fig. 5b over the tropical Atlantic Ocean is not replicated and the correlations over the eastern equatorial Pacific Ocean are weaker.

In Fig. 8, we have plotted the seasonal precipitation anomalies for FMA season from the CMAP observations and the

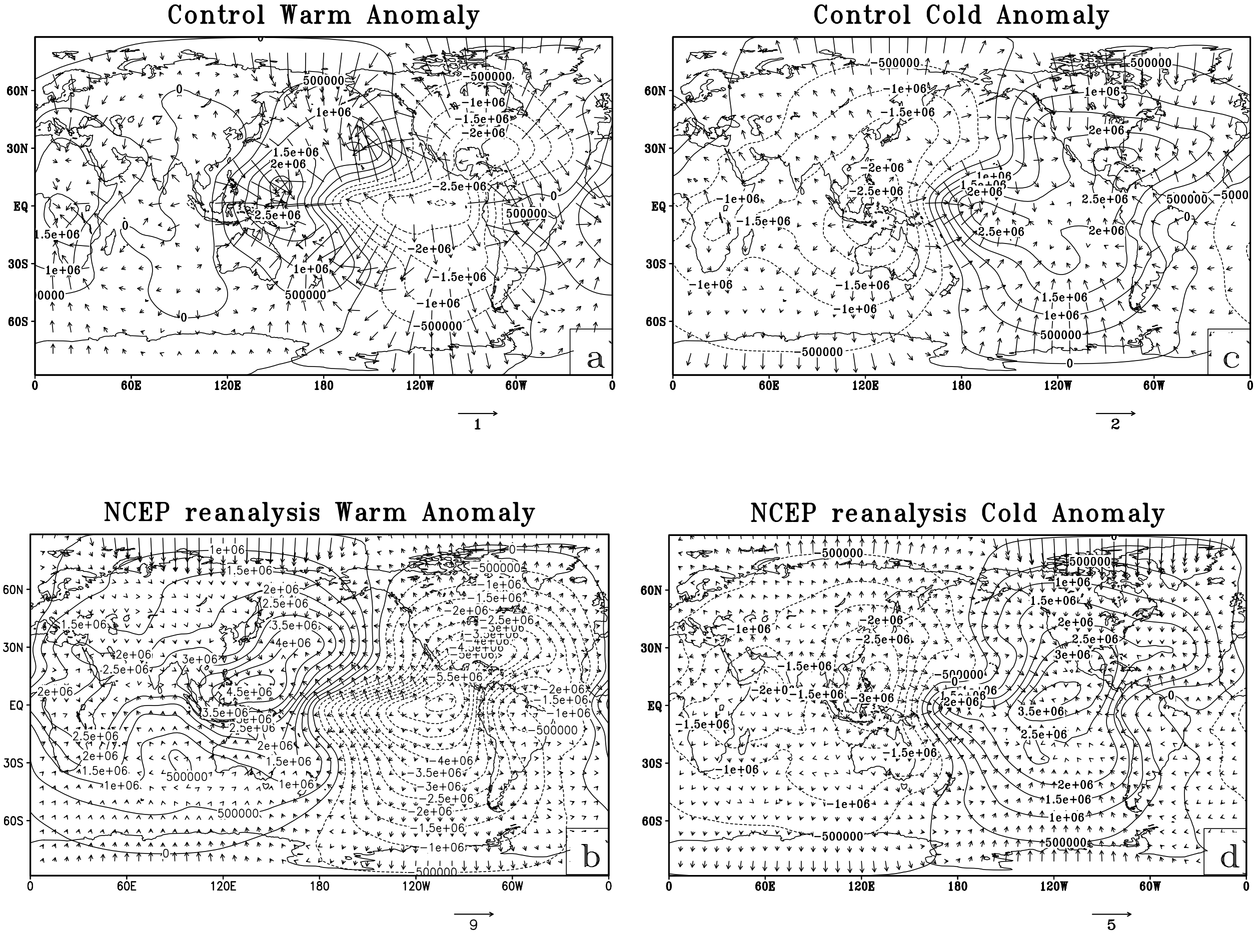

Fig. 4. The composite anomalous divergent wind and velocity potential at 200 hPa that include the warm ENSO FMA seasons of 1983, 1987 and 1992 from (a) control run, (b) NCEP reanalysis and for cold ENSO years that include the FMA season of 1985, 1989 and 1996 from (c) control run and (d) NCEP reanalysis. The isopleth interval is 5.0×10^5 m^2 s^{-1}. The unit of the wind vectors is ms^{-1}.

corresponding 19 yr of the control integration. In the legend of Fig. 8, the correlations of the control run with the CMAP observations are shown for the ensemble mean (in bold) and each of the ensemble members. Although the skill of the COLA AGCM in capturing the interannual variability of precipitation over Nordeste is relatively high, there are years when the rainfall anomalies in the model vary considerably from the observed anomalies. For example, in the FMA season of 1979, 1980, 1981, 1991, 1995, 1996 and 1997, the rainfall anomalies of the ensemble mean of the control run are opposite in sign to that in CMAP. This clearly points to the peril of relying solely on deterministic forecasts even in areas where the model displays relatively high skill forced by the slowly varying boundary conditions. In addition, Giannini et al. (2004) allude to a pre-conditioning role of the tropical Atlantic variability (TAV) to modulate the influence of ENSO teleconnection on Nordeste rainfall. In that study, they showed that when TAV evolves consistent with ENSO teleconnection (i.e. warm (cold) ENSO associated with warm (cold) tropical north Atlantic SSTA), then the TAV and ENSO add up to force large anomalies in Nordeste austral fall rainfall. This teleconnection implies a positive (negative) SST gradient in the tropical Atlantic Ocean during warm (cold) ENSO events and thereby, modulating the location of the ITCZ. However, if the meridional SST gradient in the Atlantic Ocean is negative (positive) in warm (cold) ENSO years, then Giannini et al. (2004) found from their modeling study that the Nordeste rainfall was more unpredictable.

Similar to Fig. 8 the FMA seasonal SSTA is plotted in Fig. 9 for regions outlined as EPO (Eastern Pacific Ocean), NTAO (North Tropical Atlantic Ocean) and STAO (South Tropical Atlantic Ocean) in Fig. 1. These domains approximately circumscribe areas of significant correlation between the local FMA seasonal SSTA and contemporaneous Nordeste FMA seasonal rainfall anomalies as shown in Fig. 5b. It is seen in Fig. 9 that in 95 (96) the north Atlantic SSTA is neglible (warm) when the ENSO anomaly is warm (cold) over the eastern equatorial Pacific. This is contrary to the canonical development of ENSO. In other words, the tropical Atlantic SST gradient is reversed relative to what ENSO forcing implies. This affects the predictability of the meridional excursion of the ITCZ which is the main rain-bearing

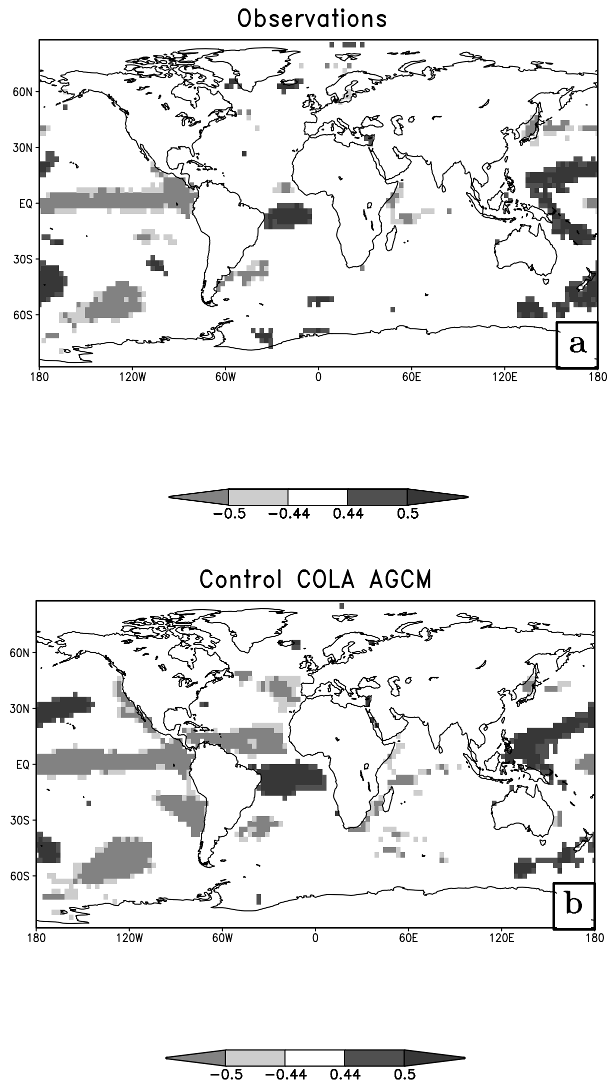

Fig. 5. The correlation of FMA seasonal precipitation anomaly over Nordeste from (a) observations and (b) control COLA AGCM run with contemporaneous observed (HADISST) SST. Correlations over the 95% confidence limit are shaded.

system of Nordeste (Giannini et al., 2004). This may explain the failure of the model to capture the rainfall anomalies over Nordeste in 95 (despite being a warm ENSO year with Niño3.4 SSTA of 1.3 in NDJ) and 96 (despite being a cold ENSO year with Niño3.4 SSTA of −0.8 in NDJ). The correlations between these SSTA are shown in Table 2. It is clear from Fig. 9 and Table 2 that the NTAO and the EPO SSTA behave coherently while the anomalies over the STAO have a sign opposite to that of the SSTA in the EPO. This is also shown in some of the past studies (Nobre and Shukla, 1996; Enfield and Mayer, 1997). However, the correlation between the NTAO and the EPO SSTA are not so high as to eliminate the variability of NTAO SSTA independent of contemporaneous SSTA in the EPO region. In Table

Table 2. The correlation of FMA SST anomalies between the various oceanic domains outlined in Fig. 1. The correlations in brackets are for EPO SST anomalies leading STAO and NTAO FMA SST anomalies by one season

	EPO	STAO	NTAO
STAO	−0.325 (−0.153)	1.0	−0.382
NTAO	0.351 (0.419)	−0.382	1.0

2, we have also shown in brackets the correlations of the tropical Atlantic SSTA with the leading November–December–January (NDJ) SSTA of the EPO. Although, the linear relationship with the STAO SST anomalies reduces, the teleconnection with the NTAO SSTA is relatively higher than the contemporaneous correlations as observed in other studies (Enfield and Mayer, 1997; Curtis and Hastenrath, 1995). In fact, in the years of 1979, 1980, 1981, 1991 and 1997 when the control AGCM displayed poor skill in simulating the FMA seasonal rainfall over Nordeste, the SSTA over the NTAO region were rather pronounced whilst the SSTA over the EPO (even over the Niño3.4) region was relatively insignificant. Chang et al. (2003) in a related study of AGCM coupled to a mixed layer ocean model showed that local thermodynamic air–sea interaction is another dominating factor in affecting climate variability in the tropical Atlantic region besides the remote influence of ENSO. In their coupled model experiment, Chang et al. (2003) show that the initial SSTA over the tropical Atlantic persist beyond a season despite the shallow mixed layer of the tropical Atlantic Ocean through reduced thermal damping and introduction of non-local effects through active air–sea feedback between surface heat flux and SST.

Therefore, in summary, even in years of strong ENSO events the COLA AGCM can display unpredictable behavior with regard to Nordeste rainfall. This follows from SSTA developing in the tropical Atlantic that have their antecedents unrelated to ENSO which cause the meridional movement of the ITCZ in the tropical Atlantic to behave contrary to the ENSO forcing.

4.3. Sensitivity experiments

As explained earlier, the control run is repeated to generate two sets of experimental runs in which climatologically varying annual SST is prescribed over the Pacific Ocean (PAC run) for one set, while in the other set it is prescribed over the Atlantic Ocean (ATL) with observed SST forcing in the rest of the ocean basins. The earlier figures of correlating the Nordeste FMA rainfall with global observed SST (Fig. 5) are repeated for the PAC and ATL runs in Figs. 10 and 11. In these figures, the observational counterpart of the teleconnection is obtained by a simple stepwise linear regression model developed from observed CMAP FMA seasonal precipitation over Nordeste with observed Pacific and Atlantic SST variabilities separately. The correlations that are over the 95% confidence interval from a standard t-test are

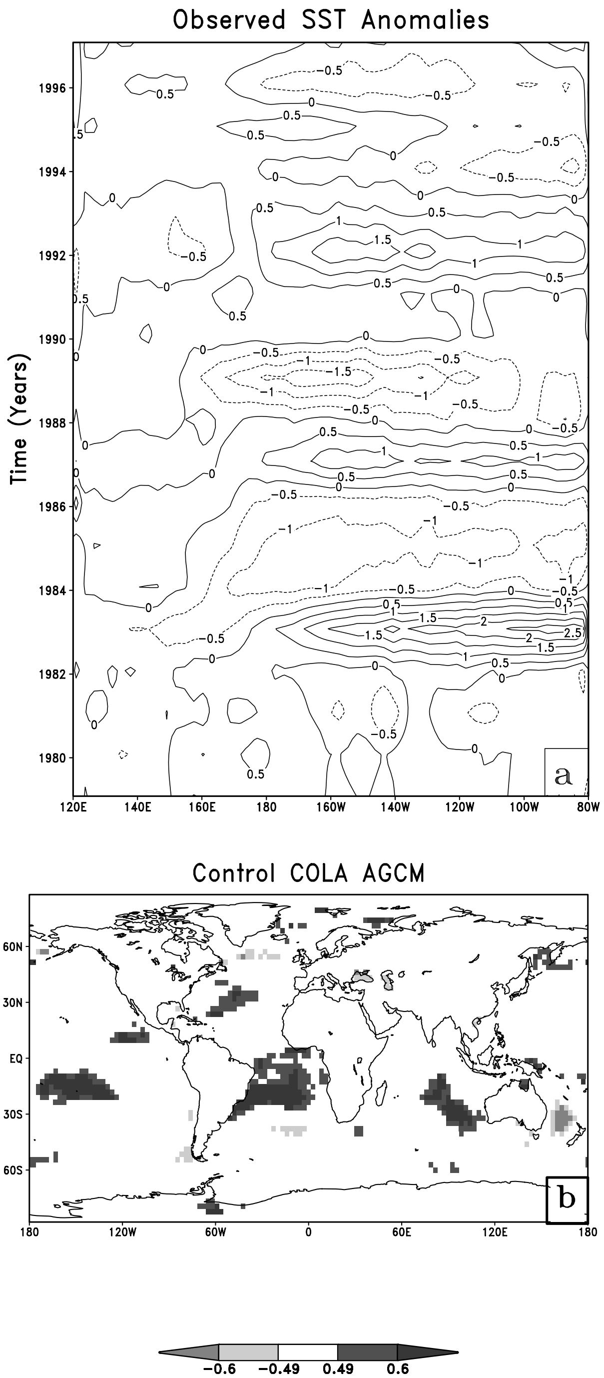

Fig. 6. (a) The FMA seasonal SSTA over equatorial Pacific Ocean from observations. (b) Same as Fig. 4b but with years of the four largest ENSO events (defined from SSTA over the Niño3 region from Fig. 4ba) removed. Correlations over the 95% confidence limit are shaded.

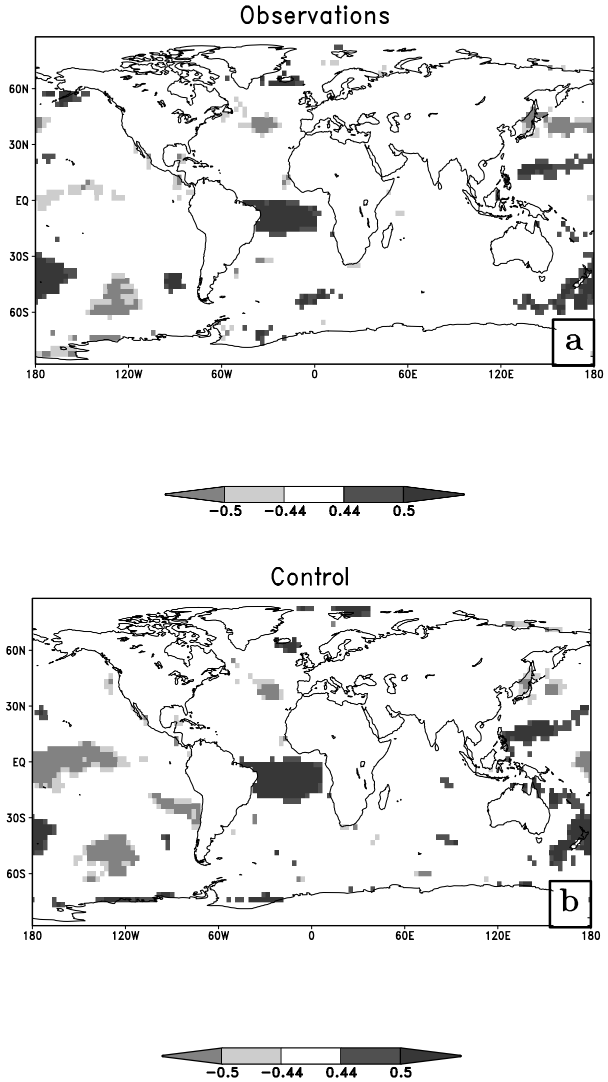

Fig. 7. The correlation of FMA seasonal precipitation anomaly over Nordeste from (a) observations and (b) control COLA AGCM run with leading NDJ observed (HADISST) SST. Correlations over the 95% confidence limit are shaded.

plotted in the figure. It is apparent from the figure (Fig. 10) that even in the absence of variability of the Pacific Ocean SST, the PAC experiment model and the simple linear regression model from observations are able to retain most of the teleconnection patterns of the control run. The appearance of the dipole structure in the linear regression model (in Fig. 10a) vis-a-vis the observed teleconnection pattern in Fig. 5a clearly indicates the interplay of the non-linearities. The correlations of the respective precipitation rate with the corresponding observed precipitation over Nordeste is indicated in the right-hand corner of the figures. It is interesting to note that both the linear regression model and the PAC run reinforce the correlation over the southern eastern Pacific region relative to Fig. 5b. The absence of this correlation in Fig. 5a suggests that the variability of Pacific SST and the associated non-linear relationship with the large-scale circulation field reduces the intensity of this teleconnection as determined from the correlations. The correlations of the FMA rainfall variability over Nordeste in the PAC run with the observed

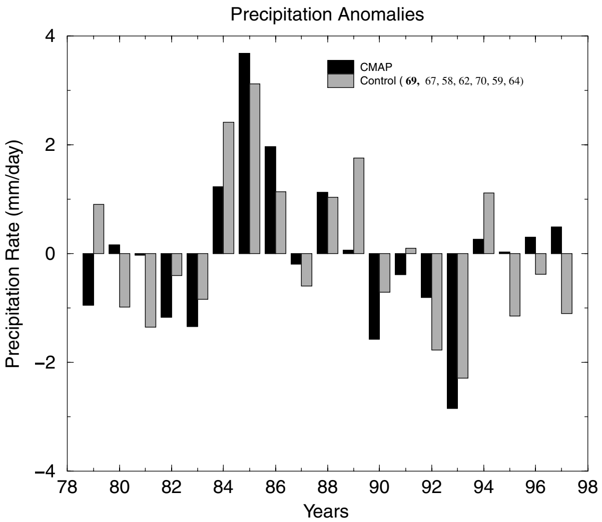

Fig. 8. The FMA seasonal precipitation anomalies over Nordeste from the control run and CMAP observations. In the legend, the correlations (in hundredths) for the ensemble mean (in bold) and for each of the six ensemble members are given.

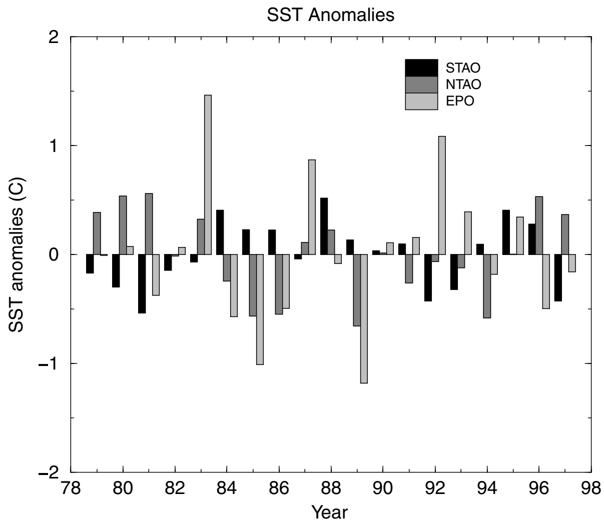

Fig. 9. The FMA seasonal SST anomalies from observations (HADISST) over the EPO, the NTAO and the STAO region (outlined in Fig. 1) are shown.

Table 3. Definition of probability thresholds used in the ROC analysis for six-member ensembles

No. of members indicating the event	Probability threshold (%)
2 or more	33
3 or more	50
4 or more	60
5 or more	83

equatorial Pacific SST in Fig. 10b clearly suggests the influence of the tropical Atlantic SSTA that is a manifestation of ENSO. This remote manisfestation of ENSO in the tropical Atlantic Ocean is accounted in some of the earlier studies. Nobre and Shukla (1996) in their observational study showed that the variation in trade wind strength preceded the development of SSTA in the tropical Atlantic Ocean. In another related study, Lau and Nath (1996) showed that the atmospheric anomalies forced by ENSO influence the trade winds in the Atlantic Ocean. This modulation in turn drives the net surface heat flux anomalies (Seager et al., 2000) that results in a local SST response which lags the Pacific Ocean SSTA by nearly one season. ENSO, by influencing the meridional gradient of SST in the tropical Atlantic Ocean, modulates the position of the ITCZ which in turn affects the Nordeste precipitation (Moura and Shukla, 1981; Hastenrath and Heller, 1977). Furthermore, it is seen that the bias in the teleconnection over the NTAO is slightly ameliorated in the PAC run.

However, in the ATL run (Fig. 11) the correlation patterns have dramatically changed showing little resemblance to either the observed (Fig. 5a) or the control model (Fig. 5b) teleconnection patterns. The ATL run clearly demonstrates the importance of the Atlantic Ocean SST variability to the Nordeste FMA seasonal rainfall. These correlations further indicate that the Nordeste rainfall variability is largely forced by the Atlantic SST variability. This result is consistent with the conclusions of other studies (Giannini et al., 2001; SC2000). It should, however, be mentioned that these stand alone AGCM experiments with prescribed SST (bereft of any coupled variability) could artificially over-emphasize the effects of the Atlantic SST variability on the Nordeste FMA seasonal rainfall. The examination of the remote influence of ENSO on the SSTA of the tropical Atlantic Ocean is beyond the scope of this study.

In Fig. 12, we have plotted the FMA seasonal precipitation anomalies over Nordeste from the PAC and the ATL runs along with observations similar to Fig. 8. The correlations in the PAC (ATL) run which are comparable (different) to that in the control integration are consistent with the teleconnection patterns in Fig. 10.

In order to investigate the sensitivity of the lag/lead relationship between Nordeste rainfall and Pacific SSTA, we have shown in Figs. 13a and b the correlation pattern of FMA rainfall with the leading NDJ global observed SSTA for the PAC and ATL runs, respectively. The teleconnections obtained from a simple stepwise linear regression model of the observed FMA seasonal rainfall over Nordeste against the leading NDJ SST were similar (not shown). We find that in the PAC run, the teleconnection with equatorial Pacific SSTA is lost and yet the deterministic skill of the model is comparable to the control run. In contrast, in the ATL run although there are significant correlations with the equatorial Pacific Ocean, its rainfall skill over Nordeste is poor. In summary, our results suggest that the direct effect of ENSO on Nordeste rainfall variability through anomalous Walker

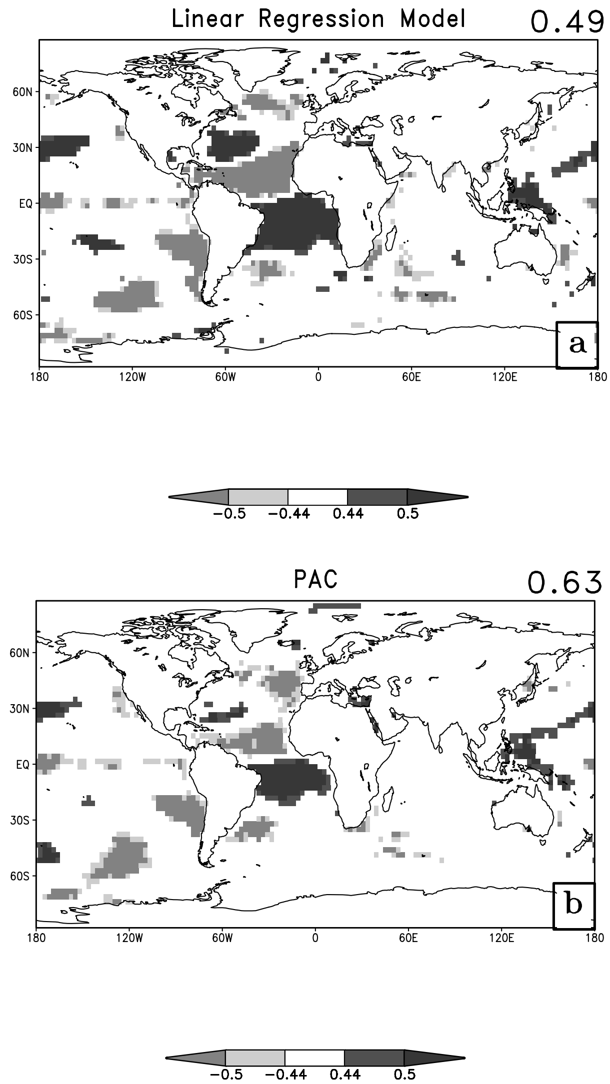

Fig. 10. Same as Fig. 4 but from (a) a linear regression model of Nordeste precipitation using only Atlantic SST variability developed from observations and (b) the PAC sensitivity run of the COLA AGCM. The correlations of the respective precipitation with the observed CMAP precipitation over Nordeste are indicated in the upper right-corner of the figures.

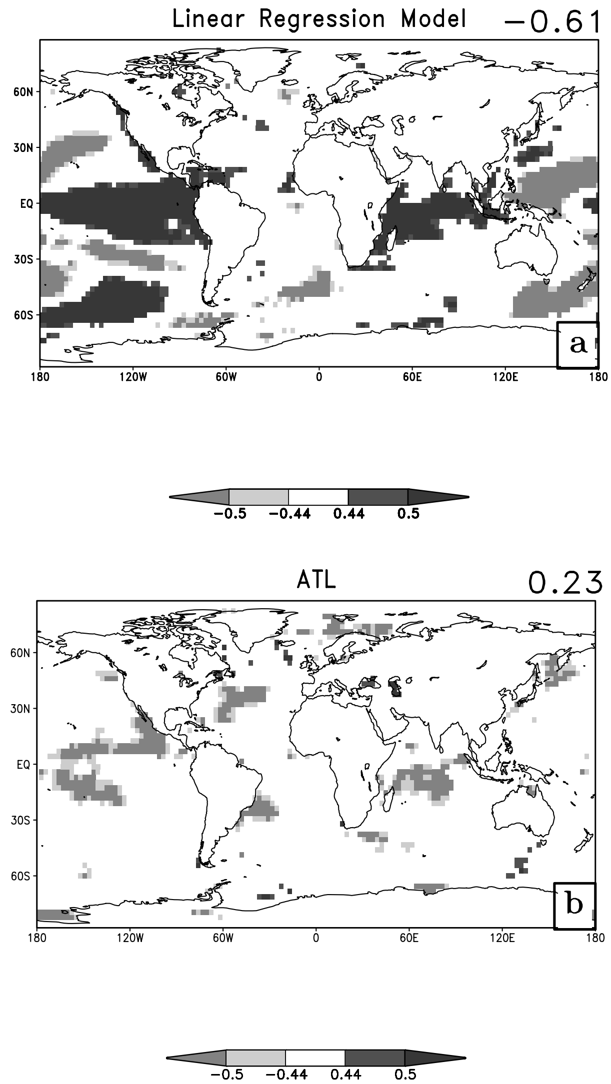

Fig. 11. Same as Fig. 7 but from (a) a linear regression model of Nordeste precipitation using only Pacific SST variability developed from observations and (b) the ATL sensitivity run of the COLA AGCM.

circulation may not be as critical. However, this result could be model dependent, especially with the prevalent systematic errors over the region and the weaker anomalous Walker circulation as seen in Fig. 4. In Fig. 14, we have shown the climatological errors of the FMA seasonal precipitation from the control COLA AGCM integration. The split ITCZ phenomenon is prevalent in both the Atlantic and the Pacific Ocean basins. Associated with this bias are weak equatorial winds (not shown). Furthermore, precipitation errors in the Amazon Basin have the bearings of the 'Gibbs' phenonmenon which also contributes to the bias in the zonal circulations. These biases lead to negligible anomalies of the zonal circulations in the COLA AGCM at the equator over this region.

4.4. *Probabilistic skill*

Although rainfall variability over the Nordeste region demonstrates a strong boundary forced signal, the COLA AGCM has failed to predict this variability in a significant number of years. This has been especially true when the ENSO signal is weak or the tropical Atlantic SST variability is contrary to the ENSO forcing. In this section, we shall assess the probabilistic skill of the COLA AGCM. Raisanen and Palmer (2001) and many other recent studies (Kirtman, 2003; Palmer et al., 2000) indicate that because of the inherent uncertainties in the climate models and

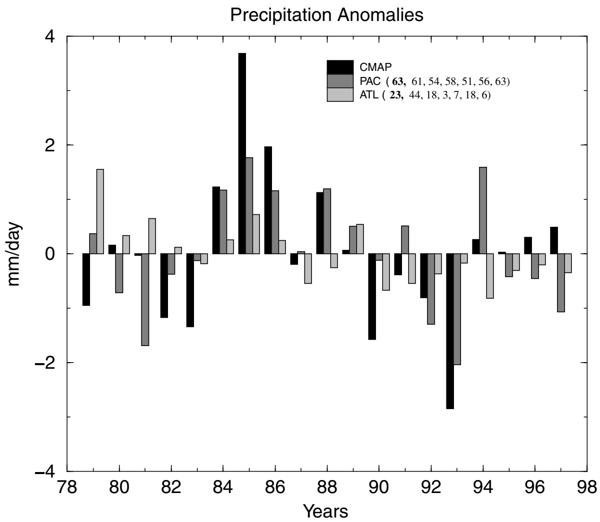

Fig. 12. Same as Fig. 5 but from the sensitivity runs (PAC and ATL) of the COLA AGCM.

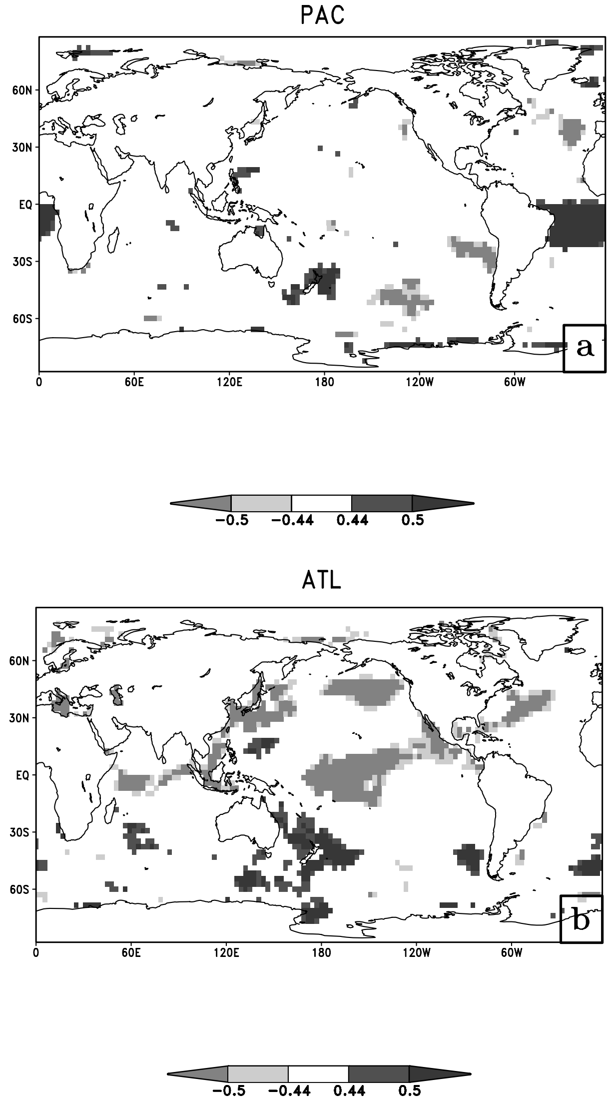

Fig. 13. Same as Fig. 4a but from the sensitivity runs of the COLA AGCM (a) PAC and (b) ATL.

the unforced chaotic climate variability, the climate forecasts should be expressed in probabilistic form. In a compelling argument, Brankovic and Palmer (1997) indicate that SSTA and other slowly varying boundary forcing impact the phase-space geometry of the whole atmospheric climate attractor rather than a single phase-space trajectory. They further suggest that this impact may be assessed from changes to the atmospheric probability distribution function over different atmopsheric states. Here, in this study the probabilistic skill will be evaluated using the relative operating characteristic (ROC) curves following Graham et al. (2000). The probability thresholds for the six-member ensembles are shown in Table 3. The probability distributions are in forms of terciles to indicate the rain probability above, near and below normal. The rains over the normal are defined as those that correspond to the third part of the greatest values of rains over Nordeste in the 19-yr period of this study; similarly, below normal are defined as the values within the third part of the driest years and near normal corresponds to the third part of the values around the climatological mean. In Figs. 9a, b and c, we have plotted the ROC curves for the control COLA AGCM runs for the occurrence of the above, below and near normal rainfall seasons. In interpreting these curves it should be noted that any point lying on or below the diagonal signifies no skill. The diagonal in the figure represents the points which signifies climatology or random forecast (Graham et al., 2000). It is clear from the figure that the model has relatively more skill in predicting the extreme seasons, especially the flooding seasons. This bias in skill could again be related to the systematic errors in the model. The prevalence of stronger (weaker) than observed southern (northern) branch of the ITCZ over the Atlantic Ocean in the COLA AGCM creates a kind of perpetual flooding conditions in the Nordeste region. This cannot be easily over-ridden by the northward shift of the ITCZ forced by the warm ENSO conditions in the eastern Pacific Ocean. Furthermore, the model has the least skill in predicting a normal season. This feature of the model having more skill in predicting extreme seasons forced by the anomalies in the lower boundary is reminiscent of other models in other regions (Chen and Dool, 1997).

5. Conclusions

In this study, an attempt has been made to diagnose the predictability of February–March–April (FMA) seasonal precipitation variability over northeast Brazil (Nordeste) from a set of (six) multi-year (19-yr) integrations of a state of the art (COLA) AGCM. It is shown that this model has a reasonable skill in simulating the FMA seasonal precipitation anomaly with anomaly

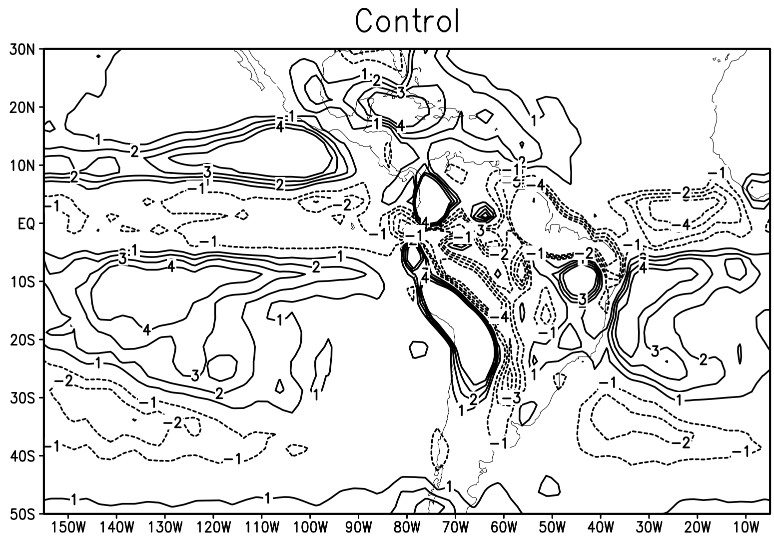

Fig. 14. The climatological errors of FMA seasonal precipitation from the COLA AGCM. The contour interval is 1 mm day^{-1}.

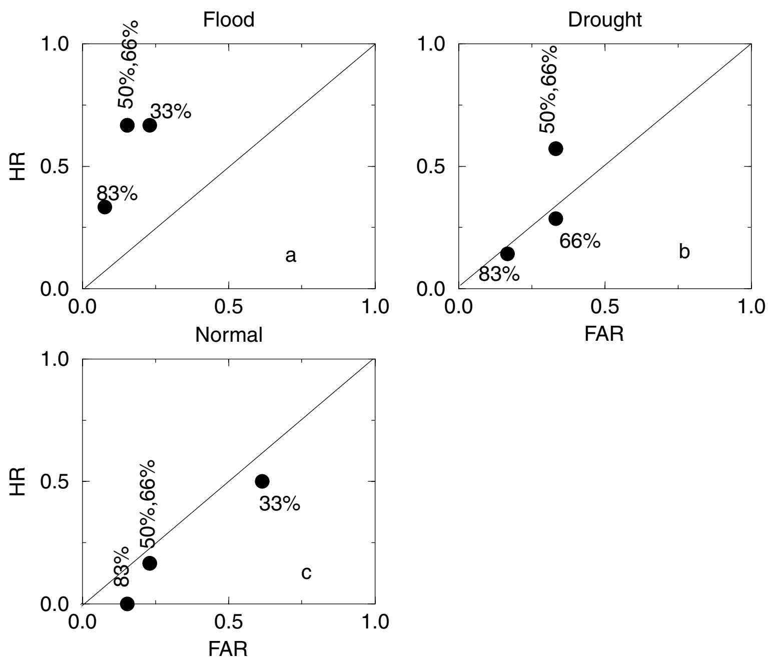

Fig. 15. The relative operating characteristic curves for the occurrence of (a) flood, (b) drought and (c) normal seasonal precipitation anomaly for FMA season from the control COLA AGCM. The probability thresholds are indicated beside the points in the graph.

correlations in excess of 0.65 (from the ensemble mean) when forced with observed SST. This skill is significantly higher than in other regions of South America and in global tropics. The objective of this study was, therefore to diagnose this high predictability displayed by the model.

The observed global teleconnection pattern indicates that precipitation in the rainy season (FMA) over Nordeste is strongly correlated with SST variations over the equatorial eastern Pacific Ocean (EPO), and the south tropical Atlantic Ocean (STAO) and the south Atlantic convergence zone (SACZ). The control COLA AGCM forced with observed SST captures this teleconnection pattern reasonably well. However, the FMA seasonal rainfall over Nordeste seems to also be correlated with SST variations in the north tropical Atlantic Ocean (NTAO) in the control run. This is found to be a result of the strong ENSO forcing simulated by the model. Although this latter teleconnection is not corroborated from the observed patterns over the period of 1979–97, it is a part of a dipole-like structure in the tropical SSTA in the Atlantic Ocean that has been the subject of investigation of some studies in the past. These studies (Nobre and Shukla, 1996; Saravanan and Chang, 2000) suggest that this dipole-like structure in the SSTA over the Atlantic Ocean is, in fact, a manifestation of ENSO variability in the Pacific Ocean. This is corroborated in this study, when this dipole-like teleconnection pattern disappears when the four largest ENSO events between 1979–97 are removed.

Sensitivity experiments with the COLA AGCM show that even in the absence of SST variability in the Pacific Ocean, the model is able to capture most of the precipitation variability in the control run over Nordeste. However, nearly all of this skill is lost when the sensitivity experiment is repeated by prescribing a climatological SST (with only annual cycle variations) over the Atlantic Ocean. These simple set of experiments suggest the importance of Atlantic Ocean SST variability on the Nordeste rainfall variability. However, because these experiments are conducted with an AGCM that is not coupled to an interactive ocean, these results may overemphasize the role of the Atlantic SST variability and ignore the indirect influence of Pacific Ocean SST variability on remote ocean basins. In fact, this study shows that even in the absence of Pacific SST variability, the teleconnection of the Nordeste FMA seasonal rainfall has significant variability that is coherent with ENSO variability over the tropical Pacific Ocean. Similar diagnosis of teleconnections of Nordeste FMA seasonal precipitation anomalies with the SSTA of the leading season (NDJ) indicate a direct influence of Pacific SST variability through anomalous Walker circulation. However, this direct influence although persistent in the PAC run does not contribute significantly to the observed Nordeste FMA rainfall variability. This could be related to the systematic errors in the model that produces the split ITCZ phenomenon and associated weak zonal wind circulations.

The probability skill analysis of the model showed that it has more skill in predicting flood years than drought with no skill in predicting normal seasons. This is also linked to the systematic errors of the model, especially the bias in producing the split ITCZ phenonmenon in the tropical Atlantic Ocean. The results of this study would suggest that improving the mean state of the AGCM will have a bearing on improved simulations of the rainfall variability over Nordeste.

6. Acknowledgments

The author wishes to thank Dr. David Straus for making useful suggestions to an earlier version of this manuscript. The author also acknowledges useful comments made by two anonymous reviewers which further improved the manuscript. This study was supported by NSF grant ATM9814295, NASA grant NAG5-11656 and NOAA grant NA16GP2248.

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