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Understanding the predictability of seasonal precipitation over northeast Brazil

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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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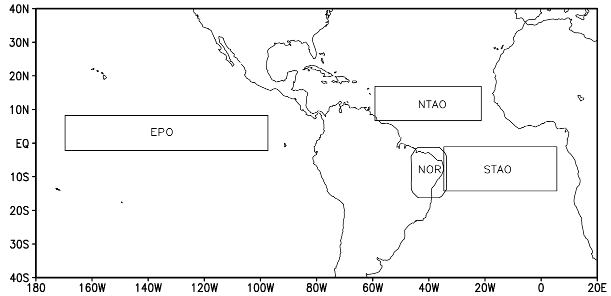

Fig. 1. The outline of Nordeste area in northeast Brazil is shown. The outline of areas denoting EPO (Eastern Pacific Ocean), NTAO (North Tropical Atlantic Ocean), STAO (South Tropical Atlantic Ocean) is also shown. The outline of these oceanic areas is derived from a discussion in Section 4.2.

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° × 1° 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.

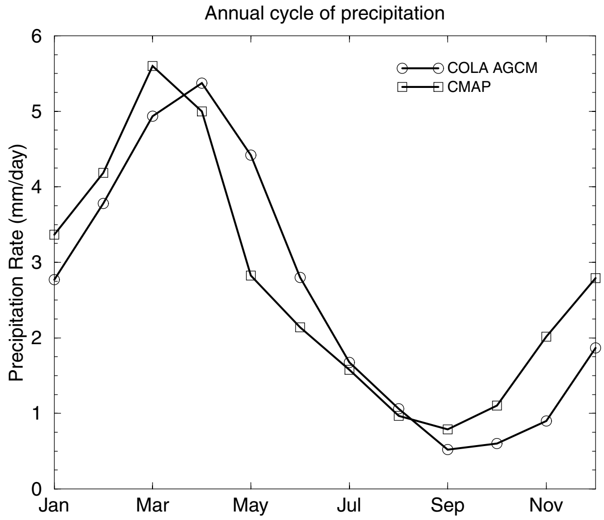

Fig. 2. The annual cycle of precipitation over Nordeste in mm day^{-1}.

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

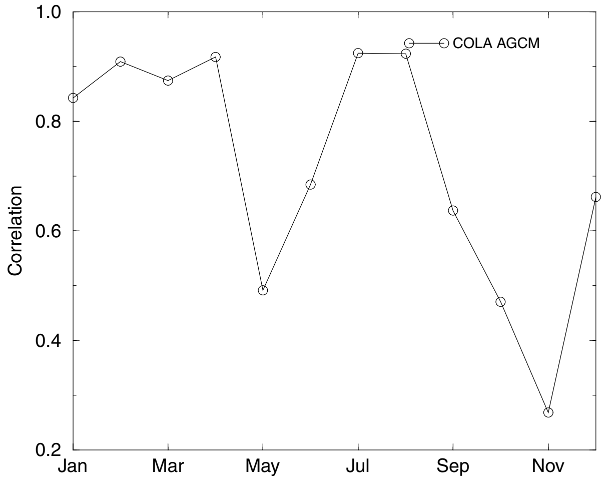

Fig. 3. The correlation of monthly anomalies of precipitation over Nordeste from the control COLA AGCM run with CMAP observations.

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