Rainfall Response in Northeast Brazil from Ocean Climate Variability during the Second Half of the Twentieth Century

Daisy Beserra Lucena, Jacques Servain, Manoel Francisco Gomes Filho

▶ To cite this version:

Daisy Beserra Lucena, Jacques Servain, Manoel Francisco Gomes Filho. Rainfall Response in Northeast Brazil from Ocean Climate Variability during the Second Half of the Twentieth Century. Journal of Climate, 2011, 24, pp.6174-6184. 10.1175/2011JCLI4194.1 . hal-00755351

HAL Id: hal-00755351
https://hal.science/hal-00755351

Submitted on 23 Oct 2021

Rainfall Response in Northeast Brazil from Ocean Climate Variability during the Second Half of the Twentieth Century

DAISY BESERRA LUCENA

Centro de Desenvolvimento Sustentável do Semiárido, Universidade Federal de Campina Grande, Sumé, Paraiba, Brazil

JACQUES SERVAIN

Institut de Recherche pour le Développement, UR 182, Université de Paris 6, Paris, France, and Visiting Scientist, Fundação Cearense de Meteorologia e Recursos Hídricos, Fortaleza, Ceara, Brazil

MANOEL FRANCISCO GOMES FILHO

Departamento de Ciências Atmosféricas, Universidade Federal de Campina Grande, Campina Grande, Paraiba, Brazil

(Manuscript received 9 November 2010, in final form 16 May 2011)

ABSTRACT

The authors investigated the rainfall variability response in northern Northeast Brazil (NNEB) from El Niño/La Niña (EN/LN) events and from the meridional sea surface temperature gradient (MGRAD) over the tropical Atlantic during the period 1948–97. The diagnostic analysis was stratified according to four climatic series of scenarios associated with EN, LN, and positive and negative MGRAD. During ENs, which were more numerous and more intense after the 1970s, the MGRAD was generally not noticeable, and the drought impact in NNEB was mainly due to the warm Pacific influence. Conversely, during LNs, the MGRAD signal was important, but there was an inverse relationship between the third and the fourth quarters of the twentieth century. Thus, before the 1970s the LNs were associated with positive MGRAD, which led to an inverse influence inducing minor changes in seasonal rainfall in NNEB. After the 1970s the LNs were linked to negative MGRAD, which induced a cumulative wet influence in NNEB. The positive MGRADs were generally associated with ENs, which reinforced the drought impact in NNEB. The well-marked negative MGRADs, which all occurred after the beginning of the 1970s, were generally linked with large LNs that induced very consistent wet episodes in NNEB. Interestingly, the two low-frequency variations in the tropical oceans observed during the second half of the twentieth century (i.e., from a few to several strong ENs and from none to numerous strong negative MGRADs) occurred concomitantly with symmetric long-term changes in the Pacific decadal oscillation (PDO) and the North Atlantic Oscillation (NAO). This symmetrical long-term climate behavior during the second half of the twentieth century could have lead to an inverse influence on the climate over the north Northeast Brazil, in agreement with a quasi-null long-term trend of the rainfall observed in that region all along this period. Such symmetrical behavior seems to have been unique during the last 150 years.

1. Introduction

The climate of Northeast Brazil (2°–14°S, 35°–46°W; see Fig. 1) is largely semiarid with noticeable seasonal and interannual rainfall variability. Exceptionally wet or dry episodes are often associated with worldwide and regional climate phenomena, such as the El Niño–Southern Oscillation (ENSO) in the equatorial Indo-Pacific Ocean (Philander 1990; Rao and Hada 1990; Trenberth 1997; Pezzi and Calvalcanti 2001; Giannini et al. 2004) and the meridional sea surface temperature gradient (MGRAD) over the tropical Atlantic (Hastenrath and Heller 1977, Markham and McLain 1977; Moura and Shukla 1981; Servain 1991; Nobre and Shukla 1996; Giannini et al. 2004).

The ENSO signal is known to be dominated by an eastward displacement of the Walker circulation inside the equatorial region from the central Pacific to the

---

Corresponding author address: Jacques Servain, FUNCEME, Ave. Rui Barbosa, 1246, Aldeota, 60115-221 Fortaleza CE, Brazil.
E-mail: jacques.servain@gmail.com

DOI: 10.1175/2011JCLI4194.1

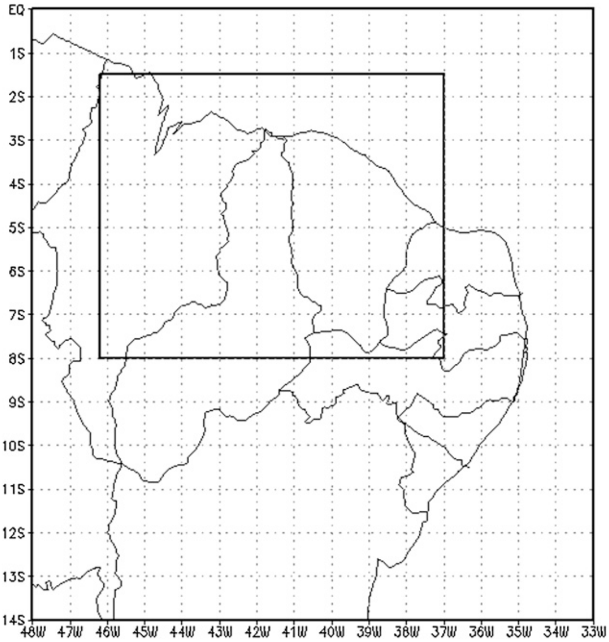

FIG. 1. Partial map of Brazil including the northern Northeast Brazil subregion.

western Atlantic (Kidson 1975; Covey and Hastenrath 1978; Giannini et al. 2000). During the positive phase of ENSO [i.e., during El Niño (EN)], there is a tendency for the inhibition of the convective system over the west tropical Atlantic that is associated with predominantly weak precipitation, especially off the coast of Northeast Brazil (Uvo et al. 1998; Saravanan and Chang 2000). Conversely, during the negative phase of ENSO [i.e., during La Niña (LN)], there is a reinforcement of the westward convective system on this oceanic region, leading to more precipitation over Northeast Brazil.

The MGRAD is represented as a latitudinal gradient in SST anomalies in the tropical Atlantic (Servain 1991; Hastenrath and Greischar 1993; Servain et al. 1999; Ayina and Servain 2003). During a standard negative phase of MGRAD, which is characterized by a negative SST anomaly and abnormal subsidence (cold sink) in the north tropical Atlantic and a positive SST anomaly and enhanced moisture convection (upward heat source) in the south, the thermal gradient is directed toward the Southern Hemisphere (Chang et al. 1997). Consequently, the intertropical convergence zone (ITCZ), characterized by a maximal level of cloudiness and precipitation, is predominantly located to the south of its climatological position. This generally brings more rain over Northeast Brazil (Wagner 1996), especially in its northern subregion (Hastenrath and Heller 1977; Markham and McLain 1977; Moura and Shukla 1981; Hastenrath 1990). Conversely, during a positive phase of MGRAD, the regular ITCZ moves northward from its normal position and the precipitation rate is often below the average in Northeast Brazil (Wagner 1996). In some instances, these changes can lead to dramatic drought in the region. Chang et al. (1997) interpreted this ocean–atmosphere relationship in the tropical Atlantic basin as a positive feedback that sustains the MGRAD. Secondary reasons for the seasonal rainfall in Northeast Brazil (especially in its northern subregion) include local deep convection, lines of instability, breeze occurrences, and atmospheric easterly waves (AEWs). For more details on the tropical Atlantic variability and its effect on rainfall, see the extensive reviews by Sutton et al. (2000) and Xie and Carton (2004).

Interestingly, during strong ENSO years, studies have shown that there is a tendency for SST changes of the same sign (i.e., positive during ENs, negative during LNs) to develop during boreal spring in the northern region of the tropical Atlantic (Nobre and Shukla 1996; Chang et al. 1998; Uvo et al. 1998; Giannini et al. 2004; Huang et al. 2005; Huang et al. 2009). These changes can be associated with positive occurrences of MGRAD (Enfield and Mayer 1997; Saravanan and Chang 2000; Andreoli et al. 2004; Andreoli and Kayano 2007; Huang et al. 2009), which increase the remote influence of the tropical Pacific Ocean over the Northeast Brazil climate variability (Giannini et al. 2004). Such a SST anomalous pattern over the tropical ocean, which is linked with changes in the large-scale zonal Walker-type and meridional Hadley-type circulations (Charney and Shukla 1981), may extend to the extratropical latitudes (Nobre and Shukla 1996; Gu and Philander 1997; Okomura and Xie 2001).

Our early basic purpose was to extend previous findings and examine the Pacific and Atlantic climatic impacts on seasonal rainfall in all of Northeast Brazil. For that, an extended study (Lucena 2008) was previously performed over the three subregions of Northeast Brazil (northern, eastern, and southern) such as they are historically classified according to seasonal climate variations and different regimes of precipitation (e.g., Hastenrath and Heller 1977; Hastenrath and Lamb 1977; Moura and Shukla 1981; Molion and Bernardo 2002). Based on this academic work, we specifically focus, in the present paper, on the northern subregion (NNEB), see Fig. 1) where the climate response to the Pacific/Atlantic combination was found as the most coherent. Complementary information on the relative climatic impact over the three subregions of Northeast Brazil can be found in Lucena et al. (2011).

The main seasonal rainfall in NNEB occurs from February to May (see Fig. 2). This corresponds to the period of time for the southernmost position of ITCZ

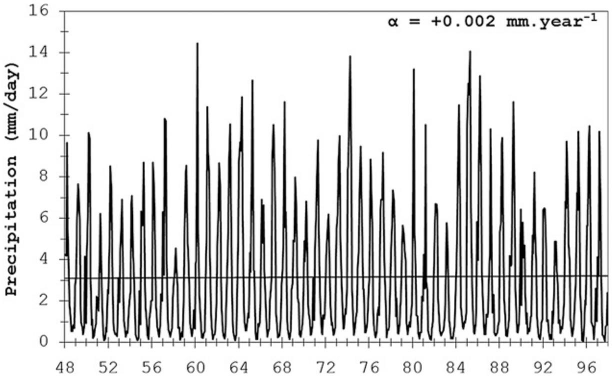

FIG. 2. 1948–97 monthly precipitation (mm day^{-1}) averaged over the NNEB subregion. The linear trend (quasi-null) is superimposed and the linear coefficient (α) is indicated.

over the Atlantic and also corresponds to the period of time that immediately follows the canonical occurrences of the El Niño and/or La Niña (LN) phenomenon. During the rest of the year (especially from July to December) precipitation over NNEB is very rare or nonexistent, as also illustrated in Fig. 2. Interesting to note, the linear trend of the rainfall precipitation over NNEB was quasi-null (+0.002 mm yr^{-1}) and insignificant during the second half of the twentieth century.

The diagnostic analysis proposed here involved four scenarios that stratified the climatic effects from EN/LN events with those from main positive/negative MGRAD episodes. The study examined the climate measurements from 1948 to 1997 when important changes in number, intensity, phase, and property of ENSO episodes were previously noted (Wang 1995; An and Wang 2000; Federov and Philander 2000; Richard et al. 2000; Wang and An 2001). Early studies have also shown that this second half of the twentieth century experienced long-term changes in the phases of the Pacific decadal oscillation (PDO) (Mantua et al. 1997; McCabe and Dettinger 1999; Graham 1994; Hare and Mantua 2000; Richard et al. 2000; Stenseth et al. 2003) and the North Atlantic Oscillation (NAO) (Hurrell 1995; Hurrell and van Loon 1997; Tanimoto and Xie 2002; Stenseth et al. 2003; Wainer et al. 2008).

After presenting, evaluating, and discussing the datasets in the following section, the core of the diagnostic analysis, structured according to the four scenarios (i.e., EN, LN, positive MGRAD, and negative MGRAD), is illustrated and discussed in the third section according to different time scales of variability. In the final section, we have provided a summary and conclusion.

2. The datasets

For this study, being mainly diagnostic, all data presented here are unfiltered and undetrended (as in Giannini et al. 2004). This allows us to better quantify the direct impact of the climate variability over the NNEB response by retaining the real amount of rainfall that is directly related to, for instance, the damage to local economy.

We used the Climate Prediction Center (CPC) precipitation dataset (Chen et al. 2002) for the rainfall observations in NNEB between 1948 and 1997 (Fig. 2). This dataset is based on a global network of in situ rain gauges interpolated according to a 2.5° × 2.5° grid (about 12 grid boxes spread over NNEB). Although the distribution of rain gauges are heterogeneous across the globe, the distribution of the rain gauge numbers is generally up to five by each grid box inside Northeast Brazil (see Fig. 4 of Chen et al. 2002).

Using the Global Sea-Ice and Sea Surface Temperature (GISST) database (Rayner et al. 2003), Fig. 3a shows the monthly time series of the Niño-3.4 index (i.e., SST anomalies in 5°N–5°S, 120°–170°W) (Trenberth 1997; Rasmusson and Carpenter 1982; Ropelewski and Halpert 1989) for the 50 years of the study period. According to a standard computation from the NOAA Climate Prediction Center, EN and LN years were classified as years in which the threshold of ±0.5°C was met for a minimum of two consecutive months from November to January using the three-month running mean of the Niño-3.4 index value. Table 1a roughly classifies (as strong, moderate, or weak) 14 selected EN episodes [4 (10) before (after) 1970] and 13 selected LN episodes [5 (8) before (after) 1970]. Although the number of strong LNs was equally balanced before and after 1970 (four strong LNs in each subperiod), the significant (1% level using a Student's *t* test) positive linear trend (+0.014°C yr^{-1}) noted in the Niño-3.4 index from 1948 to 1997 (Fig. 3a) was due to the greater number of strong EN events that occurred after the 1970s (four strong ENs versus one strong EN before 1970). This change in the ENSO signal was concomitant with a negative-to-positive long-term phase change in the PDO (Fig. 3b), which was related to a long-term warming in the tropical region of the Pacific (Graham 1994; Hare and Mantua 2000; Richard et al. 2000; Mantua and Hare 2002; Stenseth et al. 2003). Such tropical–extratropical extensions of the interdecadal climate fluctuation have previously been simulated (Gu and Philander 1997).

The years with positive or negative MGRAD were chosen based on the ''dipole'' index proposed by Servain (1991). This dipole index is estimated as the difference between the average SST in the northern tropical Atlantic (NTA), delimited by 5°N–28°N, 60°–20°W and the average SST in the southern tropical Atlantic (STA), delimited by 5°N–20°S, 35°W–5°E. These limits were

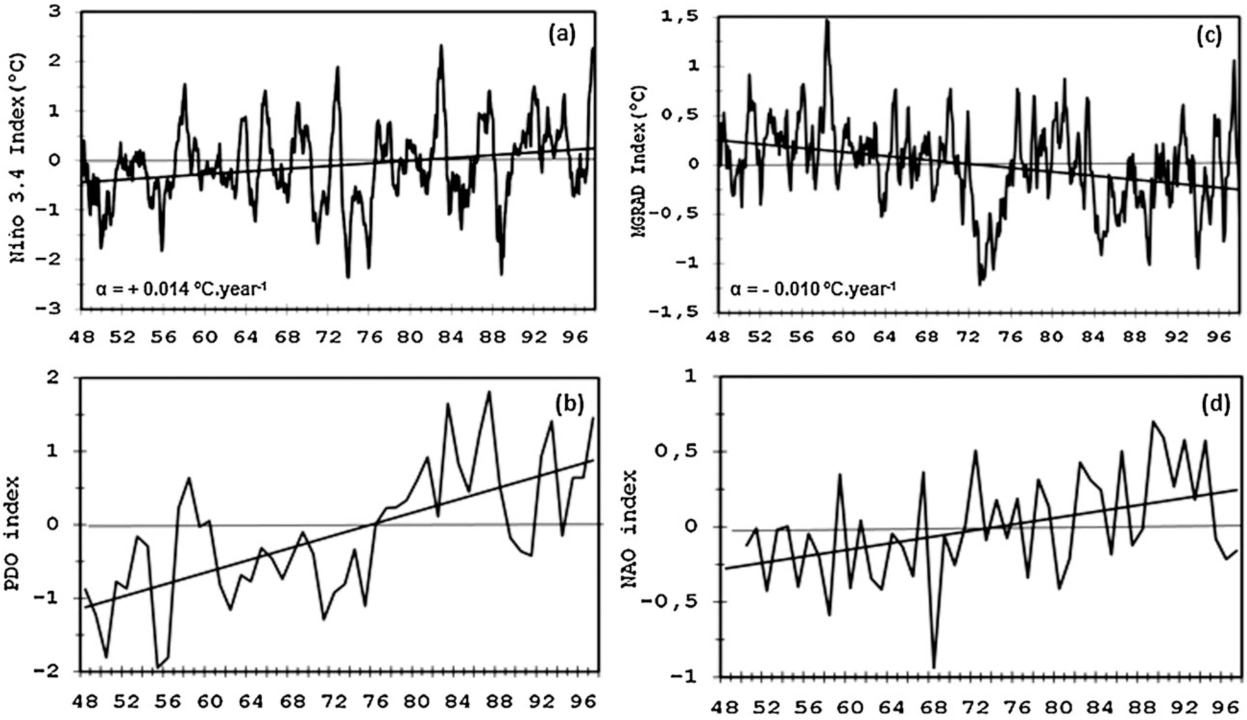

FIG. 3. (a) Monthly Niño-3.4 index (°C), (b) yearly normalized values of the PDO computed from monthly database constructed by Mantua and Hare (2002), (c) monthly MGRAD index (°C), and (d) December–March normalized values of NAO computed and updated by Hurrell (1995) for the time period 1948–97. Linear trends have been superimposed and the linear coefficients (α) are indicated for Niño-3.4 and MGRAD indices.

chosen because the SST annual ranges are very similar in these two subregions (for more details see Servain 1991). The years of positive (negative) MGRAD were considered to be when the monthly dipole index value was above +0.5°C (below −0.5°C) for at least two consecutive months between January and June. The monthly time series of MGRAD is shown in Fig. 3c. Table 1b roughly classifies (as strong, moderate or weak) a selection of 10 positive MGRAD episodes (4 before 1970 and 6 after 1970) and 9 negative MGRAD episodes (all after 1970). If we only considered the positive MGRAD yearly distribution that could be partially related to the change in the occurrences of EN episodes noted above, then more EN events after the 1970s would imply more warm episodes in NTA (i.e., a favorable condition for more occurrences of positive MGRAD) (Nobre and Shukla 1996; Uvo et al. 1998; Giannini et al. 2004). The small difference in these two numbers (6 versus 4), however, does not allow us to conclude this with certainty. Negative MGRAD episodes were only present after the 1970s (8 of the 9 events were strong), which suggests that a climatic change led to a significant (1% level Student's *t* test) negative linear trend in the MGRAD index (-0.010°C yr^{-1}) between 1948 and 1997 (Fig. 3c). The positive-to-negative shift in the MGRAD index that occurred within the middle of the second half of the twentieth century could have been directly related to the interdecadal change observed in the NAO during the same period (see Fig. 3d). Indeed, a negative phase of NAO (leading to warm SST in the NTA) between the 1940s and the 1970s was followed by a prevailing positive phase of that oscillation (leading to cold SST in NTA) during the last three decades of the twentieth century (Hurrell 1995; Hurrell and van Loon 1997; Tanimoto and Xie 2002; Stenseth et al. 2003; Giannini et al. 2004; Wainer et al. 2008).

3. Four scenarios for climatic impact in NNEB

This discussion is based on two different time scales. On the interannual time scale, we are interested in the year-to-year occurrences of climate variability in both Pacific and Atlantic tropical oceans and by their climatic responses over NNEB. Here the individual yearly episodes can be detailed, quantified, and compared basin by basin. The decadal time scale, obviously limited here to the 50 years of study, is mainly attempted thru the above-indicated long-term global climatic see-saw that was observed during the 1970s, especially in the tropical Pacific region. That approach highlights the discussion

TABLE 1. El Niño and La Niña years, and positive and negative MGRAD years classified according to a rough combination between rate amplitude and duration of event.

Year	Classification	Year	Classification
El Niño		La Niña	
1957/58	Strong	1949/50	Strong
1963/64	Weak	1950/51	Strong
1965/66	Moderate	1954/55	Strong
1968/69	Moderate	1955/56	Strong
1969/70	Moderate	1964/65	Moderate
1972/73	Strong	1970/71	Moderate
1976/77	Weak	1971/72	Moderate
1977/78	Weak	1973/74	Strong
1982/83	Strong	1974/75	Strong
1986/87	Moderate	1975/76	Strong
1987/88	Moderate	1984/85	Weak
1990/91	Strong	1988/89	Strong
1991/92	Strong	1995/96	Weak
1994/95	Moderate		
MGRAD			
Positive		Negative	
1951	Moderate	1951	Moderate
1956	Moderate	1956	Moderate
1958	Strong	1958	Strong
1966	Weak	1966	Weak
1970	Moderate	1970	Moderate
1978	Weak	1978	Weak
1980	Moderate	1980	Moderate
1981	Moderate	1981	Moderate
1983	Weak	1983	Weak
1997	Moderate	1997	Moderate

about such global features that may have different long-term impacts on the climate of NNEB.

As seen on Table 1, a positive (negative) MGRAD index was associated with an EN (LN) event for 50% of the selected cases between 1948 and 1997, which indicates a strong relationship between the climate variability of the two tropical ocean basins. Trying to avoid statistical obstacles in the interpretation of the climatic impacts of both the Pacific and Atlantic Oceans in NNEB, we analyzed in the present study four different scenarios. Each scenario was directly related to the previously selected EN, LN, positive, or negative MGRAD episodes. The behavior of the SST anomaly pattern (i.e., Niño-3.4 or MGRAD) associated with either the Pacific or Atlantic region was diagnosed over the other oceanic region during a 12-month period, which was divided into four quarters starting with September–November (i.e., before the beginning of the rainy season in NNEB). Fig. 4 shows the results related to the 14 selected ENs and the 13 selected LNs, and Fig. 5 shows the results related to the 10 selected positive MGRADs and the 9 selected negative MGRADs. In particular, we were interested in the EN/LN events during the September–November (SON) and December–February (DJF) quarters, the MGRAD events during the DJF and March–May (MAM) quarters, and the precipitation during the MAM quarter (i.e., the core of the rainy season in NNEB). Though our method of stratification of the climatic modes was similar for some aspects with the method used by Giannini et al. (2004), we were interested in the present study by the four scenarios EN, LN, positive MGRAD, and negative MGRAD, whereas in the previously cited study only the two modes attached to ENSO were discussed (with a focus on the preconditioning variability in the tropical Atlantic).

For each one of the 14 selected ENs, the quarterly Niño-3.4 index is shown in Fig. 4a. As expected, not all of the EN events developed in exactly the same way. For 9 ENs, the Niño-3.4 index remained positive during the four quarters, whereas the Niño-3.4 index quickly decreased from positive to negative values for four cases (1963–64, 1969–70, 1972–73, and 1990–91). Fig. 4b shows the NTA and STA indices computed for the same quarters as the 14 selected ENs. For most of these EN episodes, the MGRAD was nonexistent or very weak. However, two cases merit special consideration: the strong 1957–58 EN event, which was associated with a large positive MGRAD, and the strong 1972–73 EN event, which quickly changed into a negative LN episode and was associated with a strong negative MGRAD. These results indicate that an equal relationship between an EN episode and a positive meridional SST gradient over the tropical Atlantic does not happen systematically. That result must be compared to Giannini et al. (2004) where it was found that the Atlantic variability was, for most of the time, ‘‘discordant’’ with the ENs (i.e., inverse signs between EN and MGRAD).

However, the climate variability of the Atlantic can still be related to ENSO. Indeed, previous studies have shown that an EN episode can be linked to the warming of the northern part of the tropical Atlantic (i.e., the NTA domain) without any other consequence for the southern part (i.e., the STA domain) (e.g., Nobre and Shukla 1996; Chang et al. 1998; Uvo et al. 1998; Andreoli et al. 2004; Giannini et al. 2004; Huang et al. 2005; Huang et al. 2009). Moreover, the majority of the cases presented in the present study have verified that EN episodes are linked to warming of the NTA (see Fig. 4b). Furthermore, previous studies based on observations and numerical simulations (e.g., Delécluse et al. 1994) showed that strong ENs (e.g., the 1982–83 EN) could be related to subsequent warming episodes over the equatorial basin of the Atlantic (e.g., the 1984 Atlantic El Niño).

Fig. 4c shows the observed precipitation anomalies in NNEB during the same 14 EN episodes using the same

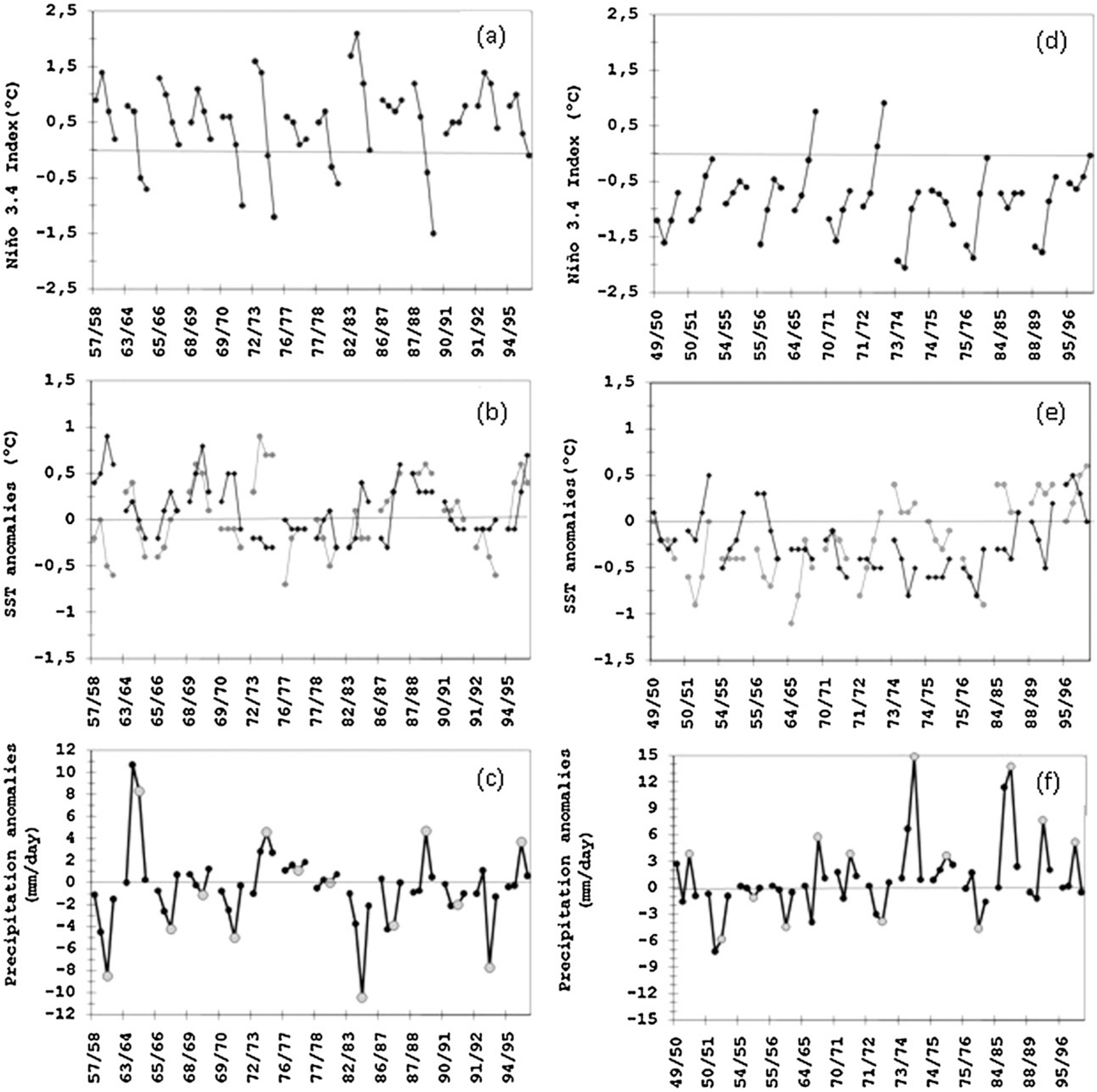

FIG. 4. Quarterly (SON, DJF, MAM, JJA) (a) Niño-3.4 index for the 14 EN events selected during the period 1948–97; (b) the NTA index (black) and STA index (gray); and (c) the observed precipitation anomaly in NNEB from CPC dataset, with a focus on MAM (gray disk). (d)–(f) as in (a)–(c) but for the 13 LN events.

quarters as in Figs. 4a and 4b. The MAM quarter, considered to be the core of the rainy season, is represented by a different symbol (gray disk). For the majority of the EN occurrences (8 versus 14 events), the precipitation was weaker than normal during MAM. This result is in agreement with the known relationship between an EN episode and a somewhat dry rainfall season in NNEB. Indeed, the three driest episodes (1957–58, 1982–83, and 1991–92) were concomitant with three strong ENs (Fig. 4a and Table 1a). However, an inverse relationship can also be seen in this analysis when five ENs were associated with wet episodes in NNEB. Indeed, the discussion of the EN scenario does not allow a definitively robust conclusion.

A similar analysis was done for the 13 LN events. The climatic behavior during these LNs (Fig. 4d) was more stable than for the ENs (Fig. 4a). For 11 of the 13 LN events, the Niño-3.4 index remained negative for at least

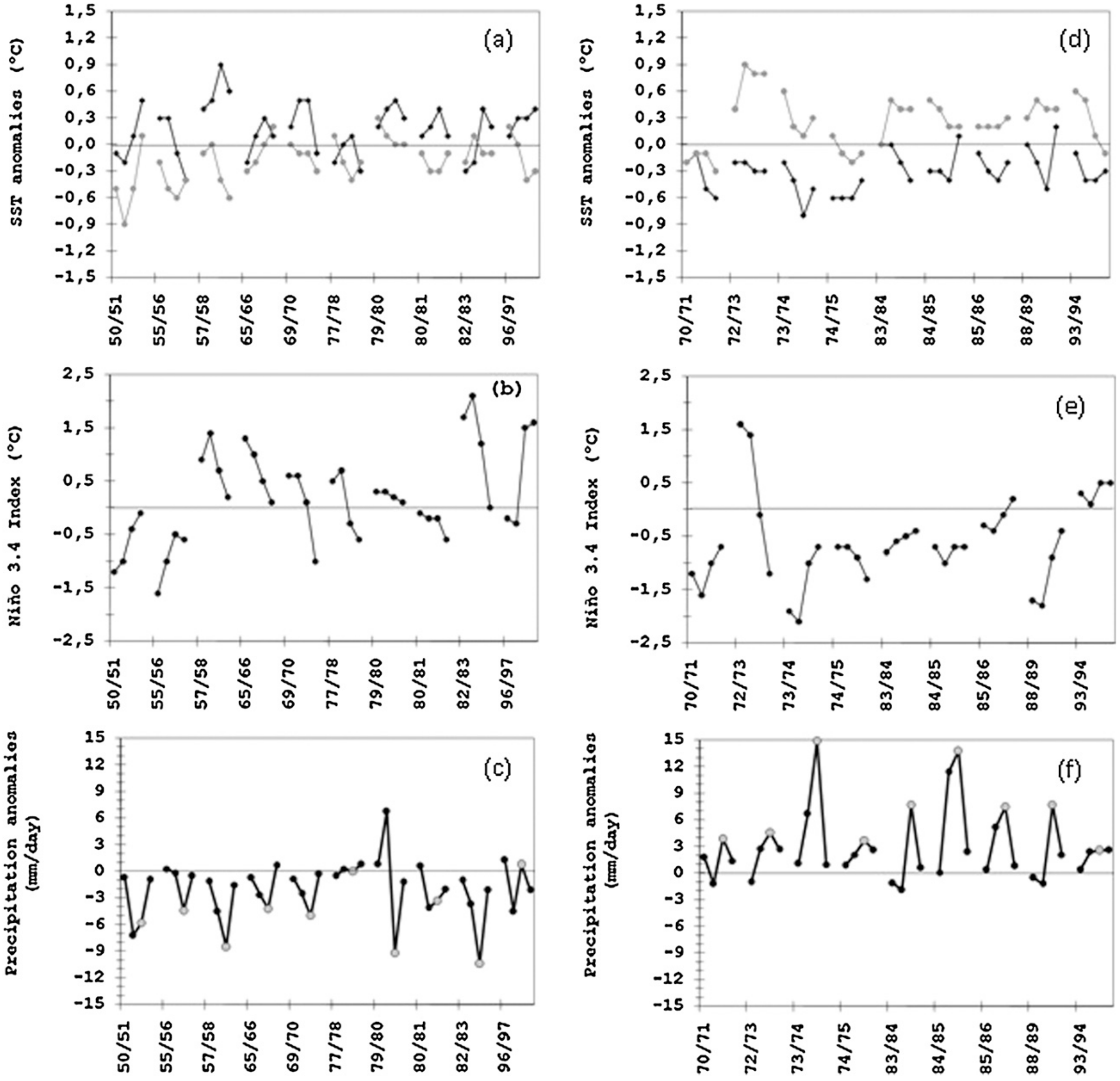

FIG. 5. Quarterly (SON, DJF, MAM, and JJA) (a) NTA index (black) and STA index (gray) for the 10 positive MGRAD events selected during the period 1948–97; (b) the Niño-3.4 index; and (c) the observed precipitation anomaly in NNEB from CPC dataset, with a focus for MAM (gray disk): (d)–(f) as in (a)–(c) but for the 9 negative MGRAD events.

12 months. The two exceptions were the LN events of 1964–65 (JJA 1965 with a positive value in the Niño-3.4 index) and 1971–72 (MMA and JJA 1972 with positive values in the Niño-3.4 index). The MGRAD behavior was also very different during the LN events (Fig. 4e) compared with the previously studied EN episodes (Fig. 4b). For most of the cases (8 versus 13), the MGRAD was well marked but there was a noticeable change around the 1970s. Indeed, the MGRAD values (see Fig. 4e) were strongly positive (discordant, according to the results of Giannini et al. 2004) during the LN events for 1950–51, 1955–56, and 1964–65, whereas this index was strongly negative (concordant) during the LN events for 1973–74, 1974–75, 1984–85, and 1988–89. Consequently, the observed rainfall response in NNEB during these 13 LN events (Fig. 4f) showed clearly differentiated impacts of the Pacific and Atlantic in NNEB. During the 1950s and 1960s, the observed rainfall anomalies in MAM, which were associated with the seven LN events that occurred during this period, did not exceed 6 mm day^{-1}. Among

these weak rainfall anomalies, three were positive, three were negative, and one was neutral. This quasi-normal response is in agreement with an inverse-forcing climatic impact from the Pacific (LN events leading to a wet response) and the Atlantic (positive MGRAD leading to dry response). Conversely, during the subsequent period (the 1970s, the 1980s, and part of the 1990s), the observed rainfall anomalies in MAM, which were associated with the LN events that occurred during this period, were positive for the greater majority of the events (5 versus 6). These results reflected a combined wet effect of the Pacific (due to LN) and the Atlantic (due to a negative MGRAD). In particular, the observed rainfall anomalies in NNEB, which were integrated from the MAM quarter of 1975 and 1985 (after LN events), reached positive values of up to 13 mm day^{-1} (Fig. 4f). Thus, the LN scenario leads to an unexpected result directly linked to long-term climate changes that occurred during the second half of the twentieth century. To note, Giannini et al. (2004) indicated that the Atlantic variability was mostly ''concordant'' with the LN occurrences; here we found that was only the case during the fourth quarter of the twentieth century: for the third quarter of that century our results are in disagreement with this previous study.

Fig. 5 shows the 10 positive and 9 negative MGRADs that were selected for the study period (Table 1b). Among the 10 positive episodes (Fig. 5a), most of them (e.g., 1955–56, 1957–58, or 1996–97) were a good representation of the meridional SST gradient. The Niño-3.4 index related to these 10 episodes is shown in Fig. 5b. Except for the two initial strongly positive MGRAD events (1950–51 and 1955–56), when the Niño-3.4 index indicated strong LN episodes (Figs. 4d and 5b), and the moderate 1980–81 positive MGRAD episode, which occurred during a weak (1980–81) cold condition in the Pacific, the other seven positive MGRAD events were associated with a warm Pacific condition. Five of these seven occurrences were already presented in the EN list (Fig. 4a). Previous studies have shown that a combination of Pacific EN and positive MGRAD in the Atlantic was associated with dry conditions in Northeast Brazil (Nobre and Shukla 1996; Enfield and Mayer 1997; Uvo et al. 1998; Saravanan and Chang 2000; Andreoli et al. 2004; Giannini et al. 2004; Andreoli and Kayano 2007), which was the case for the large majority of the 10 events described in Fig. 5c. Except for the DJF quarter in 1979–80, the rainfall anomalies were always negative (or very close to zero) for the 40 quarters associated with the 10 positive MGRAD events. This indicates a very consistent dry response of the NNEB climate when the years are stratified according to a positive MGRAD index.

As noted previously, all of the negative MGRAD episodes occurred after 1970 (Fig. 5d). With the exception of the first episode in 1970–71, which was weak, the other negative MGRAD events were in excellent conformity with the standard Atlantic dipole (a strong negative SST anomaly pattern over NTA associated with a strong positive SST anomaly pattern over STA), which remained stable for several months. This constant behavior was significantly different from the positive MGRAD scenarios (Fig. 5a) that showed a less consistent intensity and duration. For a majority (7 versus 9) of the negative MGRAD events, the Niño-3.4 index was also negative during at least three quarters, which indicated a LN condition (Fig. 5e). Among these seven occurrences, five events were already present in the LN list (Fig. 4d), which confirms the concordant LN-to-negative MGRAD relationship during the fourth quarter of the twentieth century. Conversely, the 1972–73 event, which was previously discussed when analyzing the selected EN episodes (Fig. 4a), appeared again as a nonstandard event. This 1972–73 event was the only case where a strong negative MGRAD was associated (during the two first quarters SON and DJF) with a strong EN condition. Furthermore, during the next two quarters (MAM and JJA) of 1973, the Niño-3.4 index dropped dramatically to negative values. With regard to the combined climatic effects in NNEB seasonal rainfall by the full negative MGRAD and the quasi-continual LN condition, it was not surprising that a systematic wet condition was observed (Fig. 5f). This was especially true during the MAM quarter—the peak time of seasonal rainfall in the region. Thus, the negative MGRAD scenario leads to a very robust wet impact on the seasonal rainfall in NNEB.

Complementary analyses (not shown here) carried out on the selected events from detrended time series of Niño-3.4 and MGRAD indices supported qualitatively the main results stated above at the interannual time scale. Thus, during detrended EN events the detrended MGRAD index remained rather weak and positive, whereas during detrended LNs the detrended MGRAD index evolved again differently before and after the 1970s; in the same way, warm (cold) detrended conditions on the Pacific were rather noted during positive (negative) detrended MGRAD index values. This indicates that the principal conclusions stated above about the interannual time scale remain essentially consistent when using either unfiltered or filtered time series.

4. Summary and conclusions

This study pointed out the complex relationships between the El Niño and/or La Niña in the Pacific and positive/negative MGRAD in the Atlantic, and their mutual influence in the seasonal rainfall of Northeast Brazil, especially in its northern subregion. This relationship was illustrated and discussed for the second half of the twentieth century, which experienced noticeable long-term climatic shifts in the Atlantic and Pacific Oceans around the 1970s. From our diagnostic analysis, stratified in four climatic modes, 14 ENs, 13 LNs, 10 positive MGRAD events, and 9 negative MGRAD events were selected. The present study allowed us to proceed further in several aspects that were not tackled in a similar ''stratification'' of climatic modes by Giannini et al. (2004), where only the positive and negative ENSO modes were used. In some other aspects our study led somewhat to a contradiction with those of Giannini et al. (2004).

Our main results and new insights are listed in the following.

(i) The behavior of the 14 ENs had various intensities and durations. During most of these warm Pacific events, the MGRAD was generally positive (but not with a very salient value, as that was claimed by Giannini et al. 2004). In agreement with what we expected (e.g., Huang et al. 2009), the northern part of the dipole (i.e., NTA) was significantly warmer than usual for most of the selected EN episodes, particularly at the beginning of the study period. This resulted in a weak tendency for less precipitation in NNEB.

(ii) The behavior of the 13 LNs selected in the 1948–97 period were very intense and persisted for many months. Contrary to the EN years, the meridional gradient of SST over the tropical Atlantic was well developed during these LN events but with a remarkable and interesting inversion during the 1970s (not discussed in Giannini et al. 2004): the MGRAD signal was primarily positive before the 1970s and mostly negative during the LN episodes after that decade. This change in the MGRAD signal altered the precipitation induced by the Pacific and the Atlantic in NNEB. Indeed, this region was rather dry during the LN episodes of the 1950s and 1960s, but very wet during the LN events of the 1970s, 1980s, and 1990s.

(iii) Although the majority of the 10 positive MGRAD episodes during the 1948–97 period were not very prominent, three cases (two in the 1950s and one in the 1980s) were associated with strong EN events. This cumulative dry impact from the Atlantic and the Pacific SST variabilitys led to a consistent series of eight dry years in NNEB.

(iv) The nine negative MGRAD episodes, all noted after 1970, were especially interesting. They were not only remarkable in intensity and duration, but were also often related to a large and long-lasting LN event. The combined effect of the Atlantic and the Pacific was stronger than it was for the positive MGRAD scenario. This effect induced a very significant wet signal in the seasonal rainfall in NNEB.

The previous results indicate that the climatic impact related to the tropical Atlantic seems significantly more consistent than that directly linked to ENSO. An illustration of this could be found in the sign steadiness (either negative or positive) of the observed rainfall anomaly during the cases of MGRAD events (see Figs. 5c and 5f) in comparison with sign unsteadiness during cases of ENSOs (see Figs. 4c and 4f). In fact, the main reason for the wet or dry episodes in NNEB during the 50 years of this study was the development of negative or positive MGRAD patterns. Except for very large EN or LN episodes, the Pacific influence only serves as a secondary contribution to rainfall variability. As expected, the Pacific contributes to dry episodes (EN associated with a positive MGRAD) or wet episodes (LN associated with a negative MGRAD) for two scenarios. The Pacific opposes the Atlantic influence for the two other scenarios (i.e., the EN associated with a negative MGRAD and the LN associated with a positive MGRAD). During these two last scenarios a quasi-normal condition for the rainfall season is induced.

This analysis also suggests that the low-frequency climate variability in NNEB may be remotely influenced by the oceanic region in the Northern Hemisphere beyond the tropics. The larger number of ENs (drought impact) observed after the 1970s was concomitant with a negative-to-positive long-term change in the phase of the PDO. Moreover, the present work shows that strong negative MGRAD occurrences only appeared in the tropical Atlantic after 1970. That may be related to a decadal change in the NAO index—more positive phases of NAO after the 1970s led to concomitant cold SST occurrences in the NTA (Giannini et al. 2004), which could have supported negative MGRADs and then induced conditions for strong rainfall episodes in Northeast Brazil. Thus, in conjunction with the long-term climate variability (i.e., EN/LN and MGRAD) over tropical oceans, the observed in-phase (i.e., inverse impacts) long-term variations of the PDO and NAO during the second part of the twentieth century could have inhibited their possible indirect mutual impact on NNEB seasonal rainfall. Indeed, no significant linear trend was observed in the precipitation for this region during that period (Fig. 2). The in-phase interdecadal variability between PDO and NAO indices seems to have been a distinctive characteristic of the climate during the second half of the twentieth century (e.g., see Fig. 1 of Mantua and Hare 2002 for PDO and Fig. 1 of Hurrell 1995 for NAO). Other concomitant in-phase (or out-of-phase) long-term characteristics did not seem so obvious during the first part of the twentieth century or even from the beginning of the historical in situ observed SST dataset, which started during the 1860s. It is also not easy to find a similar relationship during the early years of the twenty-first century.

Acknowledgments. We are grateful to two anonymous reviewers and the editor for their thorough and insightful reviews and recommendations. We would like also to thank Ed Sarachik and Mike McPhaden for their helpful comments during the preparation of the first and revised version, respectively. The first author (DBL) would like to acknowledge the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for its grants during the years of her Ph.D. study. This work was part of the France–Brazil scientific Project of cooperation, IRD-CNPq Clima do Atlântico Tropical e Impactos sobre o Nordeste (CATIN) (Process CNPq N°492690/2004-9). We also wish to thank the UFCG Project Clima do Atlântico tropical e o Monitoramento dos Impactos no Semi-Árido (CAMISA) and the FCPC-FINEP Project Centro de Alerta de Fenômenos Extremos (CAFE) (Process FCPC/FINEP N°01.08.06117.00) for additional funds.

REFERENCES

An, S.-I., and B. Wang, 2000: Interdecadal change of the structure of the ENSO mode and its impact on the ENSO frequency. *J. Climate,* **13,** 2044–2055.

Andreoli, R. V., and M. T. Kayano, 2007: A importância relativa do Atlântico Tropical Sul e Pacífico Leste na variabilidade da precipitação do Nordeste do Brasil. *Rev. Bras. Meteor.,* **22,** 63–74.

——, ——, R. L. Guedes, M. D. Oyama, and M. A. S. Alves, 2004: A influência da temperatura da superfície do mar dos oceanos Pacífico e Atlântico na variabilidade de precipitação em Fortaleza. *Rev. Bras. Meteor.,* **19,** 337–344.

Ayina, L.-H., and J. Servain, 2003: Spatial-temporal evolution of the low frequency climate variability in the tropical Atlantic. *Interhemispheric Water Exchange in the Atlantic Ocean,* G. J. Goni and P. Malanotte-Razzoli, Eds., Elsevier Oceanographic Series, Vol. 68, 475–495.

Chang, P., L. Ji, and H. Li, 1997: A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air-sea interactions. *Nature,* **385,** 516–518.

——, ——, ——, C. Penland, and L. Matrosova, 1998: Prediction of tropical Atlantic sea surface temperature. *Geophys. Res. Lett.,* **25,** 1193–1196, doi:10.1029/98GL00852.

Charney, J. G., and J. Shukla, 1981: Predictability of monsoons. *Monsoon Dynamics,* J. Lighthill and R. P. Pearce, Eds., Cambridge University Press, 99–109.

Chen, M., P. Xie, J. E. Janowiak, and P. A. Arkin, 2002: Global land precipitation: A 50-yr monthly analysis based on gauge observations. *J. Hydrometeor.,* **3,** 249–266.

Covey, D. L., and S. Hastenrath, 1978: The Pacific El Niño phenomenon and the Atlantic circulation. *Mon. Wea. Rev.,* **106,** 1280–1287.

Delécluse, P., J. Servain, C. Levy, L. Bengtsson, and K. Arpe, 1994: On the connection between the 1984 Atlantic warm event and the 1982–1983 ENSO. *Tellus,* **46A,** 448–464.

Enfield, D. B., and D. A. Mayer, 1997: Tropical Atlantic sea surface temperature variability and its relation to the El Niño–Southern Oscillation. *J. Geophys. Res.,* **102,** 929–945.

Federov, A. V., and S. G. H. Philander, 2000: Is El Niño changing? *Science,* **228,** 1997–2002.

Giannini, A., Y. Kushnir, and M. A. Cane, 2000: Interannual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean. *J. Climate,* **13,** 297–311.

——, R. Saravanan, and P. Chang, 2004: The preconditioning role of tropical Atlantic variability in the development of the ENSO teleconnection: Implications for the prediction of Nordeste rainfall. *Climate Dyn.,* **22,** 839–855.

Graham, N. E., 1994: Decadal-scale climate variability in the tropical and North Pacific during the 1970s and 1980s: Observations and model results. *Climate Dyn.,* **10,** 135–162.

Gu, G., and S. G. H. Philander, 1997: Interdecadal climate fluctuations that depend on exchange between the tropics and extratropics. *Science,* **275,** 805–807.

Hare, S. R., and N. J. Mantua, 2000: Empirical evidence of North Pacific regime shifts in 1977 and 1989. *Prog. Oceanogr.,* **47,** 103–146.

Hastenrath, S., 1990: Prediction of Northeast Brazil rainfall anomalies. *J. Climate,* **3,** 893–904.

——, and L. Heller, 1977: Dynamics of climatic hazards in Northeast Brazil. *Quart. J. Roy. Meteor. Soc.,* **102,** 77–92.

——, and P. J. Lamb, 1977: *Climatic Atlas of the Tropical Atlantic and Eastern Pacific Ocean.* University of Wisconsin Press, 112 pp.

—— and L. Greischar, 1993: Circulation mechanisms related to Northeast Brazil rainfall anomalies. *J. Geophys. Res.,* **98,** 5093–5102.

Huang, H.-P., A. W. Robertson, and Y. Kushnir, 2005: Atlantic SST gradient and the influence of ENSO. *Geophys. Res. Lett.,* **32,** L20706, doi:10.1029/2005GL023944.

——, ——, ——, and S. Peng, 2009: Hindcasts of tropical Atlantic SST gradient and South American precipitation: The Influences of the ENSO Forcing and the Atlantic Preconditioning. *J. Climate,* **22,** 2405–2421.

Hurrell, J. W., 1995: Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science,* **269,** 676–679.

——, and H. van Loon, 1997: Decadal variations in climate associated with the North Atlantic Oscillation. *Climatic Change,* **36,** 301–326.

Kidson, J. W., 1975: Tropical eigenvector analysis and the Southern Oscillation. *Mon. Wea. Rev.,* **103,** 187–196.

Lucena, D. B., 2008: Impacto dos Oceanos Pacífico e Atlântico no Clima do Nordeste do Brasil. Ph.D. thesis, Universidade Federal de Campina Grande, Campina Grande, PB, Brazil, 225 pp.

——, J. Servain, and M. F. Gomes Filho, 2011: Avaliação do impacto de eventos climáticos extremos nos oceanos Pacífico e Atlântico sobre a estação chuvosa no Nordeste do Brasil. *Rev. Bras. Meteor.,* **26,** 287–294.

Mantua, N. J., and S. R. Hare, 2002: The Pacific decadal oscillation. *J. Oceanogr.,* **58,** 35–44, doi:10.1023/A:1015820616384.

——, ——, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteor. Soc.,* **78,** 1069–1079.

Markham, C. G., and P. R. McLain, 1977: Sea surface temperature related to rain in Ceará, Northeast Brazil. *Nature,* **265,** 320–322.

McCabe, G. J., and M. D. Dettinger, 1999: Decadal variations in the strength of ENSO teleconnections with precipitations in the Western United States. *Int. J. Climatol.,* **19,** 1399–1410.

Molion, L. C. B., and S. O. Bernardo, 2002: Uma revisão da dinâmica das chuvas no Nordeste Brasileiro. *Rev. Bras. Meteor.,* **17,** 1–10.

Moura, A. D., and J. Shukla, 1981: On the dynamics of droughts in Northeast Brazil: Observations, theory and numerical experiments with a general circulation model. *J. Atmos. Sci.,* **38,** 2653–2675.

Nobre, P., and J. Shukla, 1996: Variation of sea surface temperature, wind stress and rainfall over the tropical Atlantic and South America. *J. Climate,* **9,** 2464–2479.

Okomura, Y., and S.-P. Xie, 2001: Tropical Atlantic air–sea interaction and its influence on the NAO. *Geophys. Res. Lett.,* **28,** 1507–1510.

Pezzi, L. P., and I. F. A. Calvalcanti, 2001: The relative importance of ENSO and tropical Atlantic sea surface temperature anomalies for seasonal precipitation over South America: A numerical study. *Climate Dyn.,* **17,** 205–212.

Philander, S. G., 1990: *El Niño, La Niña, and Southern Oscillation*. Academic Press, 289 pp.

Rao, V. B., and K. Hada, 1990: Characteristics of rainfall over Brazil: Annual variations and connections with the southern oscillation. *Theor. Appl. Climatol.,* **42,** 81–91.

Rasmusson, E. M., and T. H. Carpenter, 1982: Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Mon. Wea. Rev.,* **110,** 354–384.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res,* **108,** 4407, doi:10.1029/2002JD002670.

Richard, Y., S. Trzaska, P. Roucou, and M. Rouault, 2000: Modification of the southern African rainfall variability/ENSO relationship since the late 1960s. *Climate Dyn.,* **16,** 883–895.

Ropelewski, C. H., and M. S. Halpert, 1989: Precipitation patterns associated with the high index phase of Southern Oscillation. *J. Climate,* **2,** 268–284.

Saravanan, R., and P. Chang, 2000: Interaction between tropical Atlantic variability and El Niño–Southern Oscillation. *J. Climate,* **13,** 2177–2194.

Servain, J., 1991: Simple climatic indices for the tropical Atlantic Ocean and some applications. *J. Geophys. Res.,* **96,** 15 137–15 146.

——, I. Wainer, J. R. McCreary, and A. Dessier, 1999: Relationship between the equatorial and meridional modes of climatic variability in the tropical Atlantic. *Geophys. Res. Lett.,* **26,** 485–488.

Stenseth, N. C., G. Ottersen, J. W. Hurrell, A. Mysterud, M. Lima, K.-S. Chan, N. G. Yoccoz, and B. Ådlandsvik, 2003: Studying climate effects on ecology through the use of climate indices: The North Atlantic Oscillation, El Niño Southern Oscillation and beyond. *Proc. Roy. Soc. London,* **270,** 2087–2096.

Sutton, R. T., S. P. Jewson, and D. P. Rowel, 2000: The elements of climate variability in the tropical Atlantic region. *J. Climate,* **13,** 3261–3284.

Tanimoto, Y., and S.-P. Xie, 2002: Inter-hemispheric decadal variations in SST, surface winds, heat flux and cloud cover over the Atlantic Ocean. *J. Meteor. Soc. Japan,* **80,** 1199–1219.

Trenberth, K. E., 1997: The definition of El Niño. *Bull. Amer. Meteor. Soc.,* **78,** 2771–2777.

Uvo, C. B., C. A. Repelli, S. E. Zebiak, and Y. Kushnir, 1998: The relationship between tropical Pacific and Atlantic SST and Northeast Brazil monthly precipitation. *J. Climate,* **11,** 551–562.

Wagner, R. G., 1996: Mechanisms controlling variability of the interhemispheric sea surface temperature gradient in the tropical Atlantic. *J. Climate,* **9,** 2010–2019.

Wainer, I., J. Servain, and G. Clauzet, 2008: Is the decadal variability in the tropical Atlantic a precursor to the NAO? *Ann. Geophys.,* **26,** 4075–4080.

Wang, B., 1995: Interdecadal changes in the El Niño onset in the last four decades. *J. Climate,* **8,** 267–285.

——, and S.-I. An, 2001: Why the properties of El Niño changed during the late 1970s. *Geophys. Res. Lett.,* **28,** 3709–3712.

Xie, S.-P., and J. A. Carton, 2004: Tropical Atlantic variability: Patterns, mechanisms, and impacts. *Earth Climate: The Ocean-Atmosphere Interaction. Geophys. Monogr.,* Vol. 147, Amer. Geophys. Union, 121–142.