Diagnostic Studies of Rainfall Anomalies in Northeast Brazil

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ABSTRACT

The large-scale atmospheric circulation of the Brazil–Atlantic sector is studied in relation to extreme rainfall anomalies in two large regions of Northeast Brazil (Nordeste). Long-term rainfall series, aerological records of stations in South America, and ship observations over the tropical Atlantic form the data base for this study.

Departure patterns of meteorological elements over the Atlantic are investigated for composites of extremely dry and wet years in the southern and northern Nordeste. *Southern Nordeste*'s peak rainy season is around November/December. The wet years in the southern Nordeste are marked by negative pressure departures over the South Atlantic, weak onshore southeast trades and anomalously cold waters along the south Brazil coast. These features appear to be related to Southern Hemispheric frontal systems. During the dry years, departure patterns are nearly reversed to those of the wet years. *Northern Nordeste* receives its maximum rainfall in March/April. Rainfall variations are modulated by the latitudinal displacement of the baric trough and confluence axis over the equatorial Atlantic and concomitant sea surface temperature anomalies. Case studies of recent extreme years indicate the possible existence of a local meridional circulation. The more northerly position of the convergence band over the Atlantic, the anomalously cold waters to the south of the equator and the subsidence in the southern portion of the thermally-induced meridional circulation cell over the Nordeste, characteristic of drought years, are all unfavorable for rainfall in Northeast Brazil.

1. Introduction

Variations of circulation and climate in low latitudes have attracted considerable attention in recent years. Northeast Brazil stands out prominently among the tropical regions as an area in which rainfall undergoes a dramatic change from year to year. The severe 1958 drought in particular is remembered for its serious socio-economic consequences. Such events exemplify the need to understand the dynamic causes of drought and to develop a basis for its prediction.

The climatic hazards of Northeast Brazil (Nordeste) have long stimulated the curiosity of researchers in Brazil (Sampaio Ferraz, 1950; Serra, 1956). In recent years the climate and circulation of the northern Nordeste (Fig. 1) have been studied by Namias (1972), Ratisbona (1976), Hastenrath and Heller (1977), Markham and McLain (1977), and Moura and Shukla (1981). Namias (1972) proposed an interconnection between rainfall in Ceará and cyclonic activity over the subpolar North Atlantic. Hastenrath and Heller (1977) demonstrated that extreme hydrometeorological events in northern Northeast Brazil are related to the equatorward expansion of the North and South Atlantic highs, the location of the enclosed confluence axis and cloudiness and precipitation belts over the western tropical Atlantic, as well as sea surface temperature (SST) anomalies in the tropical Atlantic. Markham and McLain (1977) likewise found a high correlation between rainfall and South Atlantic SST. Moura and Shukla (1981) conducted an experiment with the GLAS General Circulation Model, using as input an SST anomaly pattern as demonstrated by Hastenrath and Heller (1977). They concluded that the juxtaposition of a warm anomaly in the North Atlantic and cold anomaly in the South Atlantic is conducive to a thermally direct circulation with subsidence over Northeast Brazil and the adjacent equatorial Atlantic. Annual rainfall in the southern portion of the Nordeste differs remarkably from that of the northern Nordeste (Ratisbona, 1976). Kousky and Chu (1978) hypothesized that the circulation components involved in rainfall production vary between these two regions. Therefore, a mosaic of regional studies seems desirable, whereby the rainfall anomalies in the southern and northern Nordeste are analyzed in relation to variations in the large-scale circulation.

The present study utilizes a large data set described in Section 2 to investigate the extreme climatic events in the Nordeste and associated surface circulation over the Atlantic as well as upper air circulation over tropical South America. Section 3 describes general

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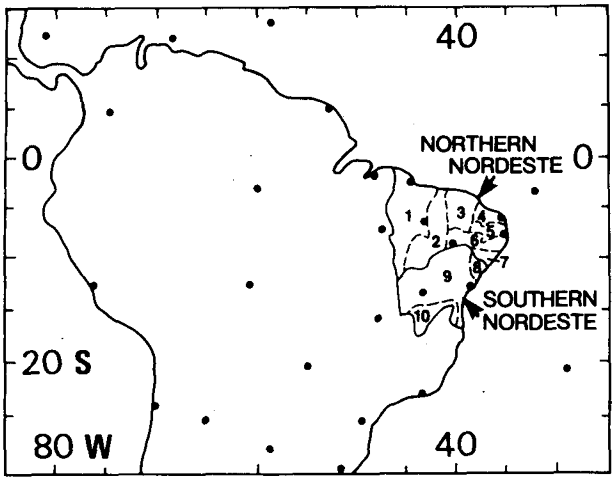

FIG. 1. Orientation map. States in Northeast Brazil are numbered as follows: 1 Maranhao, 2 Piaui, 3 Ceará, 4 Rio Grande do Norte, 5 Paraiba, 6 Pernambuco, 7 Alagoas, 8 Sergipe, 9 Bahia and 10 northern Minas Gerais. Upper air stations are shown by dots.

circulation anomaly patterns for composites of extreme years in the southern and northern Nordeste. These are complemented by case studies using recent upper air data in Section 4. The objective of this investigation is to shed light on the mechanisms of climate anomalies in Northeast Brazil through analysis of prominent large-scale circulation patterns. Earlier investigations on the northern Nordeste are confirmed and expanded, while for the southern Nordeste it will become apparent that the general circulation mechanisms of rainfall anomalies are more complex and less amenable to analysis from the available observations. However, complementing the more complete picture for the northern Nordeste, it is desirable to identify the gaps in understanding for the southern Nordeste.

2. Observations and data processing

Northeast Brazil (Nordeste) is divided into two large regions according to different annual precipitation: northern and southern Nordeste (Fig. 1). For southern Nordeste, time series of monthly rainfall totals at 40 stations for the period 1912–67 were obtained from Superintendencia do Desenvolvimento do Nordeste (Recife, Pernambuco, Brazil, 1969). Data from these stations were also collected for 1968–77 (Recife, Pernambuco, Brazil, 1978, unpublished). This region includes the entire states of Bahia and Sergipe and the northern extreme of Minas Gerais.

For northern Nordeste, the 40 stations selected in the earlier study by Hastenrath and Heller (1977) were used. Data for the period 1912–58 are available in published form (Superintendencia do Desenvolvimento do Nordeste, Recife, Pernambuco, Brazil, 1969). Records for 1959–78 were also obtained from Superintendencia do Desenvolvimento do Nordeste. Accordingly, the available base period is 1912–78. This collection consists of rainfall stations from the states of Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco and Alagoas (Fig. 1).

Selected aerological stations in Brazil and adjacent parts of South America are shown in Fig. 1 (U.S. Weather Bureau, 1968–79). This data set contains mean monthly resultant wind at the 850 and 200 mb levels.

Ship observations over the tropical Atlantic between 30°N and 30°S during the period 1911–72 available from the TDF-11 file of the National Climatic Center at Asheville, North Carolina, have been processed for one degree square areas (Hastenrath and Lamb, 1977). Subsequently, data were compiled into five degree square average values, the latter file being used in the present study. Elements of interest here include sea level pressure (SLP), wind direction and speed, and sea surface temperature (SST). For details information on these elements, reference is made to Hastenrath and Lamb (1977). Ship wind observations from the TDF-11 file covering the same area of the tropical Atlantic became available for the additional years 1973–78.

In the southern Nordeste, the rainfall series for 14 stations located in the same climatic regime were analyzed by season from July to June in accordance with the November–January rainy season. Thus, the twelve month period extends from mid-dry season to mid-dry season. For the northern Nordeste, the seasonalized rainfall data from September to August were taken from Hastenrath and Heller (1977). In addition to the aforementioned two regions, a third rainfall regime, confined narrowly along the coast from 5–18 S, where the rainy season is found in the Southern Hemisphere winter. Since it receives abundant rainfall (Kousky and Chu, 1978) and has relatively low year-to-year variability (Kousky, 1979), this region is not included in the analysis.

A regional hydrometeorological index is constructed according to

$$\bar{X}_i = \frac{1}{J_i} \sum_j X_{ij},$$

where $\bar{X}_i$ denotes the mean annual rainfall total at station i for all seasonalized years J_i, j the individual seasonalized year, and X_{ij} the rainfall totals at station i for year j. The standard deviation is

$$\sigma_i = \left[\frac{1}{J_i} \sum_j (X_{ij} - \bar{X}_i)^2\right]^{1/2}.$$

Normalization is achieved by

$$Y_{ij} = (X_{ij} - \bar{X}_i)/\sigma_i,$$

where Y_{ij} is called the normalized departure. Finally, the regional index is written as

$$R_j = \frac{1}{I_a} \sum_i Y_{ij},$$

where I_a is the number of stations available during the year j.

The rainfall indices for the southern and northern Nordeste are plotted in Fig. 2 in time series form. From the rainfall index series for the southern Nordeste, extreme years are identified as follows: **1913** (i.e., July 1912 to June 1913), **15**, 28, 32, **39**, 42, 52, 53, *59*, 62, as DRY; and **1914**, 16, **19**, 24, **26**, 43, 45, *57*, 60, 69 as WET (years in boldface being extreme). For all ten dry years R_j is less than -0.8σ, and for the ten wet years it is greater than $+0.7\sigma$. For the northern Nordeste, Hastenrath and Heller (1977) identified extreme years as follows: **1915** (i.e., September 1914–August 1915), **19**, 30, 31, 32, 36, **42**, 51, 53, and *58*, as DRY; and **1917**, 21, 22, **24**, 26, 34, **35**, 40, **64** and 67 as WET (boldface years being extreme). For all ten dry years R_j is less than -0.5σ or beyond, and for the ten wet years it is equal to or larger than $+0.7\sigma$.

3. Surface circulation during regional extreme events

Maps showing departure of meteorological elements (SLP, u, v, and SST) over the tropical Atlantic were compiled from composites of the ten driest and wettest years as depicted in Fig. 2. Departures are defined with respect to the 60 year mean. The statistical significances of the departure patterns were evaluated with respect to the reference years, namely the collective of all except the ten most dry and the ten most wet years.

a. Statistical test

The Student-t test was used to compare the means of pairs of samples. This test is based on the premise that two samples are 1) independently drawn from the population, 2) that they both possess normal distribution, and 3) that they have common variance. These premises must be verified before application of the t-test.

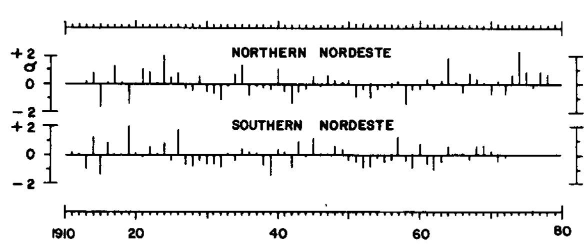

FIG. 2. All-station average of normalized departure of annual rainfall for the southern (July–June) and northern (September–August) Nordeste. Values are ascribed to the later calendar year.

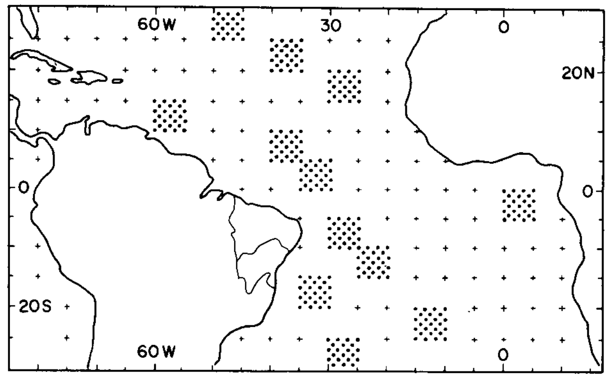

FIG. 3. Dot raster indicates 5° blocks for which statistical testing was performed.

1) In order to ascertain independence of data, 12 five degree blocks were chosen for which series of SLP, u, v, and SST are examined. The position of these areas is fairly evenly distributed over the Atlantic, with exactly one area located in each degree latitude band (Fig. 3). Autocorrelation coefficients of the SLP, u, and v are found to be near zero from one year to the next. This supports the independence of samples. By contrast, the SST series possess large autocorrelations from year to year; failing to satisfy the assumption of independence, the SST are not subjected to the t-test.

2) The distributions of SLP, u, v, and SST are found to be approximately normal.

3) The results of the F-test also validate the common variance assumption for SLP, u, v, and SST.

As the SST series do not fulfill the aforementioned premise, only the series of SLP, u, and v have been subjected to the t-test. The null hypothesis (H_0) was established that the mean value of a given element during the composite of reference years (μ_{ref}) was equal to the mean value during the extreme years (μ_{ext}). The opposite is true for the alternative hypothesis (H_1). The aforementioned hypotheses can be expressed as

$$H_0: \quad \mu_{\text{ext}} = \mu_{\text{ref}},$$

$$H_1: \quad \mu_{\text{ext}} \neq \mu_{\text{ref}},$$

where subscripts "ext" refer to the composite of extreme years, and "ref" the reference years.

According to DeGroot (1975), the statistic U is defined as

$$U = \frac{(m+n-2)^{1/2}(\bar{X}_m - \bar{Y}_n)}{\left(\frac{1}{m} + \frac{1}{n}\right)^{1/2} (S^2_{\text{ext}} + S^2_{\text{ref}})^{1/2}},$$

where m and n are the degrees of freedom associated with the sample of m extreme years and the sample of n reference years, respectively.

$$S_{ext}^2 = \sum_{i=1}^{m} (X_i - \bar{X}_m)^2, \quad s_{ref}^2 = \sum_{i=1}^{n} (Y_i - \bar{Y}_n)^2.$$

Since the ship data are available during the period 1911–72, ideally m would be equal to 20 and n equal to 84 for the two-month ensembles used to represent the peak rainy season in each year. The $\bar{X}_m$ and $\bar{Y}_n$ are respectively the average of all individual monthly values available from the ensembles for the set of extreme years (20 monthly values) and the set of reference years (84 monthly values). Using two different calendar months in each ensemble has the advantage of enlarging the sample, although the variance is being contributed to by the month-to-month persistence. Thus, the test tends to underestimate the significance of departure patterns. Since the alternative hypothesis (H_1) is two-sided, the likelihood ratio test procedure would be to reject H_0 if either $U < c_1$, or $U > c_2$, where c_1 and c_2 are constants chosen, for convenience, symmetrically with respect to zero ($c_1 < 0$, $c_2 > 0$). Accordingly, when H_0 is true, $Pr(U < c_1) = Pr(U > c_2) = \alpha_0/2$, where α_0 is the 5% level of significance in this study.

The following example illustrates the application of this test. Consider that for SLP in some oceanic region the null hypothesis H_0: $\mu_{ext} = \mu_{ref}$ is rejected at the 5% significance level. This is interpreted as a difference significant at the 5% level between the mean SLP during the extreme years and the mean SLP during the reference years. It is recognized, however, that a certain portion of area exceeding 5% of the entire domain may be necessary to claim field significance, because of the combined effects of the spatial coherence of variables and the finite number of the sample. This reservation has been discussed by Douglas *et al.* (1982) and Livezey and Chen (1983).

b. Southern Nordeste

The mechanisms of extreme rainfall events (DRY and WET) in the southern Nordeste are explored in terms of the large-scale departure patterns (Figs. 4 and 5) of SLP, SST, u (westerly positive), and v (southerly positive). Conditions during extreme years in the southern Nordeste are further illustrated by the position of the equatorial trough over the Atlantic (Fig. 6A), the line separating southerlies and northerlies (Fig. 6B), and meridional profiles of SLP (Fig. 7), zonally averaged for 25–55°W.

In order to clarify the signs of u and v departure patterns described subsequently in the text, a brief introduction of the long-term averaged u and v fields

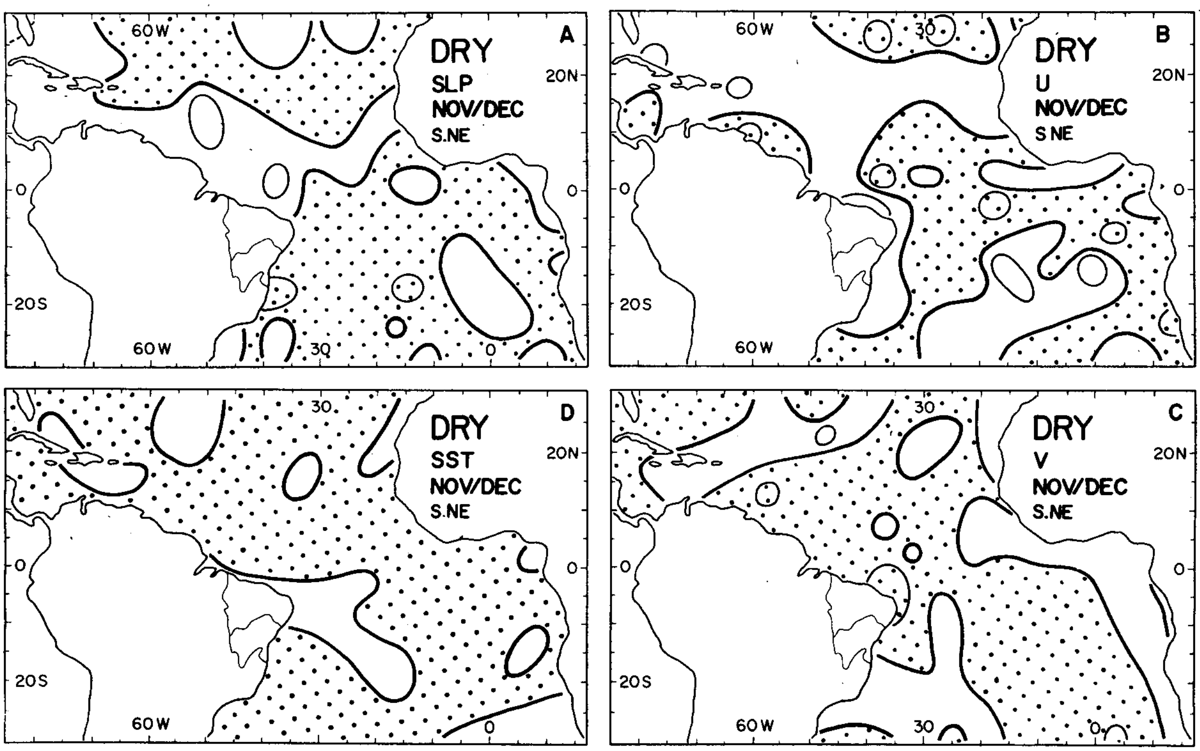

FIG. 4. November/December composite of the ten extremely dry years (DRY) in the southern Nordeste expressed as departure from the 60 year mean. (A) sea-level pressure; (B) zonal wind component; (C) Meridional wind component; (D) sea surface temperature. Positive areas are shaded with heavy solid line denoting zero departure. Thin solid line refers to the 5% significance level.

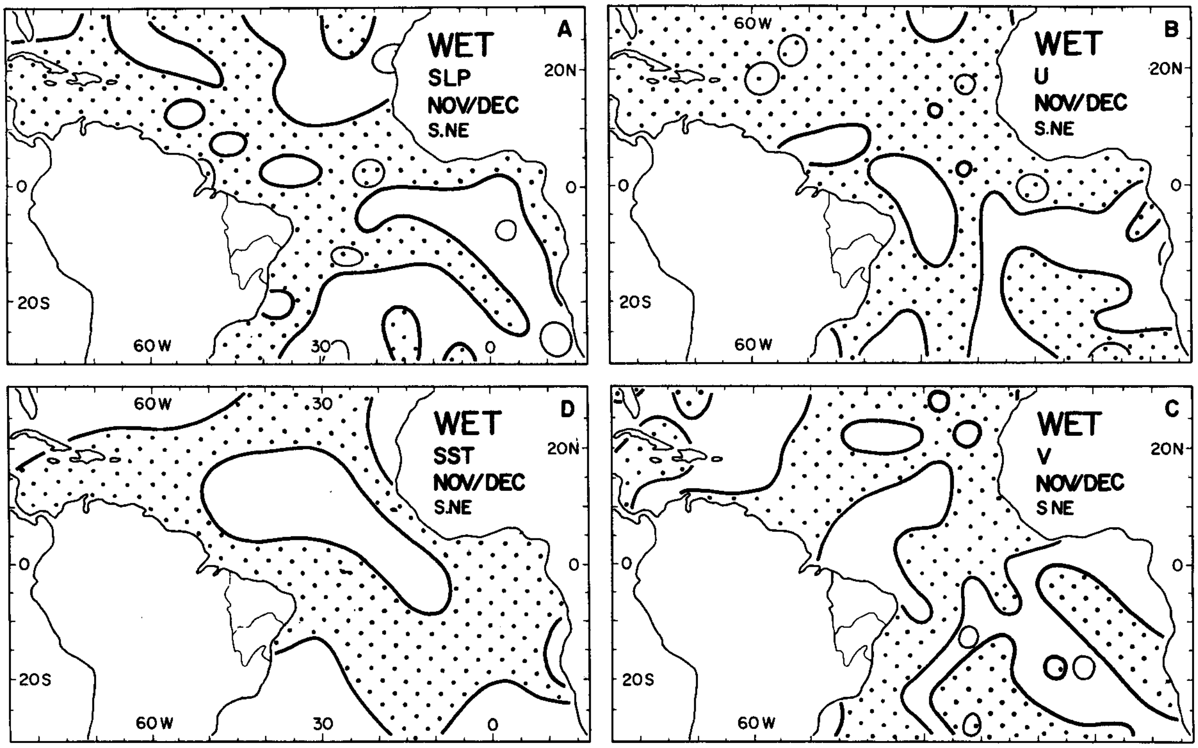

FIG. 5. November/December composite of the ten extremely wet years (WET) in the southern Nordeste. Symbols as in Fig. 4.

is necessary. For details, refer to Hastenrath and Lamb (1977). The zonal wind pattern is characterized by an easterly flow component over the Atlantic throughout the year, except near the Gulf of Guinea where flow is directed eastward. The patterns of meridional wind show that northerly components dominate over the North Atlantic, and southerlies occupy a large part of the South Atlantic. Northerlies prevail on the western side of the South Atlantic subtropical high during most of the year, except in late Southern Hemisphere fall when southerly components become prominent.

Fig. 4 depicts the circulation departures in November/December at the height of the southern Nordeste rainy season for the composite of ten extremely dry years as identified in Section 2. The SLP map (Fig. 4A) shows positive departures on the equatorward side of the South Atlantic high (SAH) and a further northward position of the equatorial trough; the latter feature also being evidenced by Fig. 6A. Meridional profiles of SLP in Fig. 7 show for the dry composite a deeper equatorial trough and a steeper meridional pressure gradient in the vicinity of the equator than for the long-term average. The map of zonal wind, Fig. 4B, shows anomalously strong easterly flow along the Brazil coast from Rio de Janeiro to the mouth of the Amazon and in the center of the South Atlantic, but weak easterlies over a large portion of the equatorial Atlantic. The map of meridional wind (Fig. 4C) shows enhanced southerly component over the eastern South Atlantic and along the northern Nordeste coast, and stronger northerlies along the southeast Brazilian coast. The SST pattern, Fig. 4D, exhibits positive departures over the Atlantic and small pockets of negative departure elsewhere.

The departure patterns in the pressure and wind fields thus consistently indicate an anomalously far northerly position of the equatorial trough and associated cross-equatorial flow from the Southern Hemisphere. This ensemble of departure configurations for the dry composite is accordingly considered meteorologically significant. Regarding the statistical significance, a t-test was applied to the fields of SLP, u, and v. Lower significance thresholds are attained over larger regions, but the 5% confidence level is reached only over limited areas.

Fig. 5 shows the November/December circulation departures during extremely wet years. The SLP map (Fig. 5A) indicates a negative departure over the South Atlantic, and a positive departure over the equatorial Atlantic. The filling of the equatorial trough is also apparent in the meridional SLP profile of Fig. 7. The meridional pressure profile differs conspicuously between dry/wet years in the southern Nordeste. In Fig. 5B, easterlies appear weakened over the western South Atlantic and most of the North Atlantic, but strengthened along the south Brazilian coast. Fig. 5C displays weakened northerlies along the

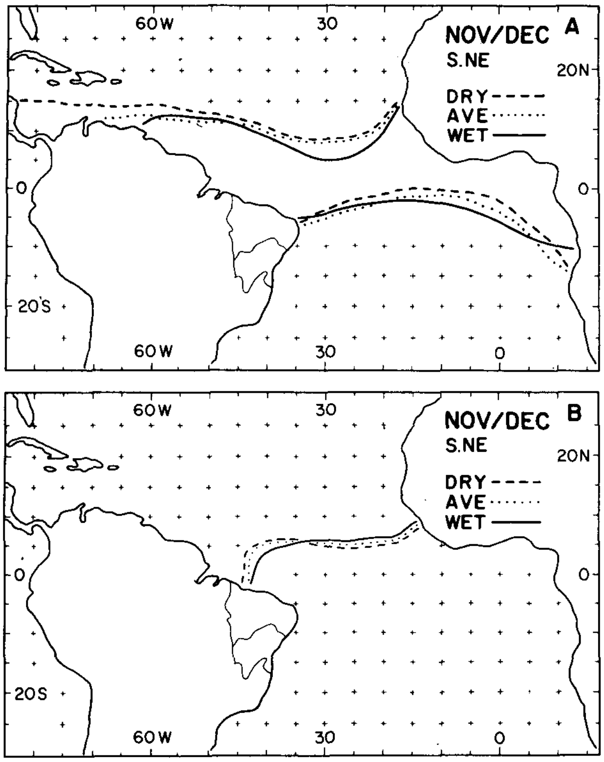

FIG. 6. November/December composite of the equatorial circulation components during extreme years in the southern Nordeste. (A) mean position of the equatorial trough as delineated by the 1012 mb isobar; and (B) mean position of the line separating southerly and northerly wind components. Dashed, solid and dotted lines refer to the composites of ten extremely dry, and ten extremely wet years in the southern Nordeste, and the 1911–70 average, respectively.

east Brazilian coast. There is some indication for a more southerly position of the line separating southerlies and northerlies over the western equatorial Atlantic during wet years as compared to dry years (Fig. 6B). Again, the departure patterns in pressure and wind fields are regarded to be of meteorological significance, although the conventional 5% statistical fiducial limit is not reached.

In a previous study, Kousky and Chu (1978) have suggested that much of the precipitation in interior Bahia is associated with frontal systems. Moreover, Kousky (1979) analyzed surface continental records for a 10 year period and noted that frontal activity may account for the maximum rainfall in November/December in the southern Nordeste. During the wet years, the South Atlantic is marked by negative pressure departures (Fig. 5A), and at such time weak easterly flow prevails along the coast of Brazil (Fig. 5B). The meridional wind along the south Brazilian coast shifts to a southerly direction (Fig. 5C), and this change is coincident with the appearance of anomalously cold water along the coast (Fig. 5D). The large SST contrast along the East Brazilian coast and the appearance of southerlies may be associated with temperate latitude frontal systems. During the dry years, the South Atlantic high is stronger than in the 60 year mean (Fig. 4A), and the southern Nordeste is characterized by strong easterlies which would obstruct the approach of weather systems from the south. Furthermore, strong northerlies prevail from the southern end of Nordeste to southern Brazil, keeping out southern cyclonic systems (Ratisbona, 1976, p. 227). The region of positive SST departure from southern Nordeste coast down to 30°S coincides approximately with the area of the enhanced northerlies (Figs. 4C and 4D).

c. *Northern Nordeste*

Hastenrath and Heller's (1977) study of the dynamics of hydrometeorological hazards in the northern Nordeste is here complemented in the following two respects: 1) Their analysis based on data for one degree square areas is substituted with a five degree square resolution, so as to facilitate comparison with another regional investigation in the present study. We have found from experience that the five degree resolution is warranted in terms of data stabiity and economy. 2) Expanding on their study, departure patterns are subjected to statistical testing.

Figure 8 displays the circulation departures in March/April for composite of ten extremely dry years in the northern Nordeste. The SLP map, Fig. 8A, indicates the more equatorward extension of the South Atlantic high, more northerly position of the trough over the western equatorial Atlantic (see also Fig. 10A), and the poleward retraction of the North Atlantic high. The latter feature is also apparent in the meridional transect, Fig. 11. Fig. 8B shows a band of increased easterlies stretching from the eastern

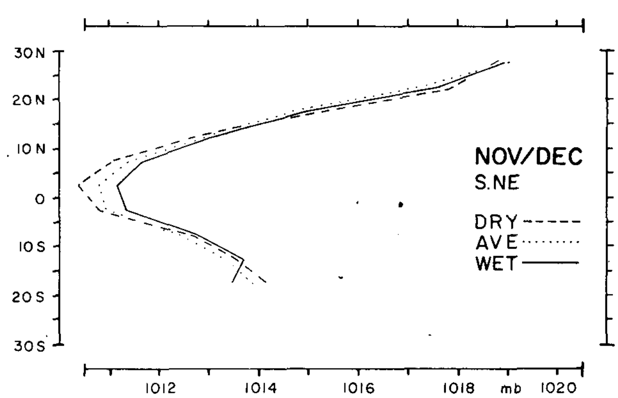

FIG. 7. November/December composite meridional profiles of sea-level pressure, zonally averaged for 25° and 55°W, during extreme years in the southern Nordeste. Dashed, solid and dotted lines refer to the composites of ten extremely dry and ten extremely wet years in the southern Nordeste, and the 1911–70 average, respectively.

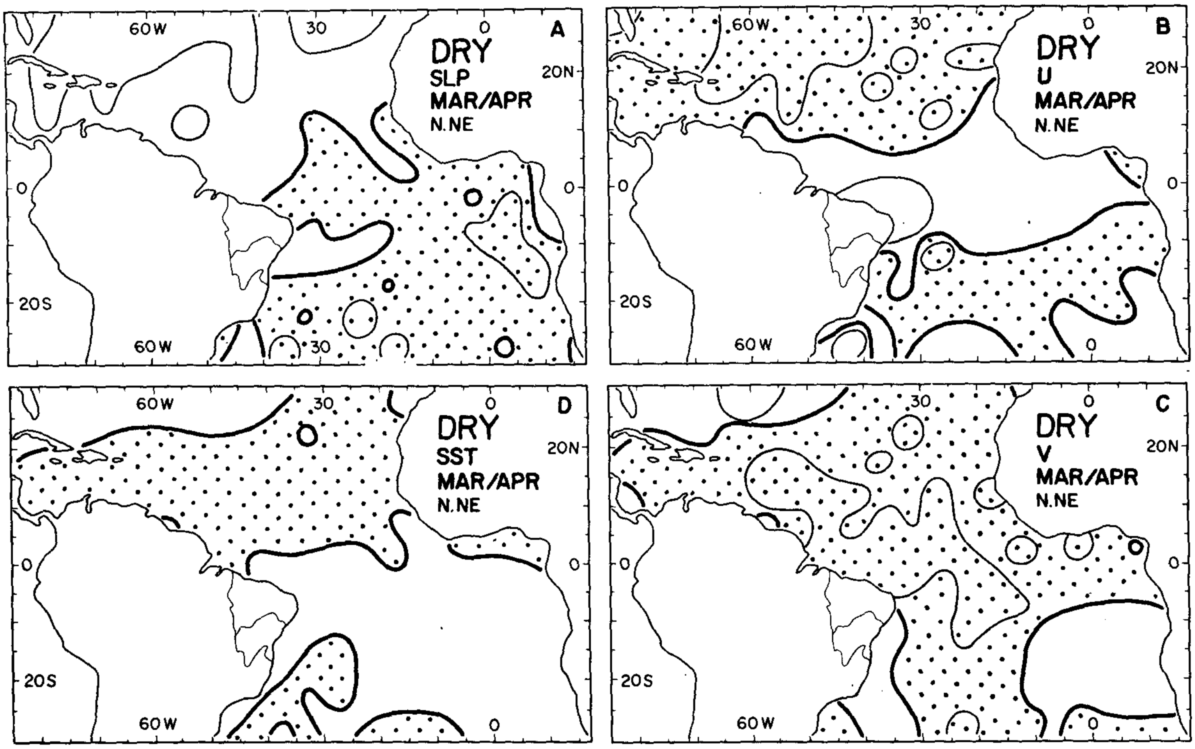

FIG. 8. March/April composite of ten extremely dry years (DRY) in the northern Nordeste. Symbols as in Fig. 4.

equatorial Atlantic to the coast of the northern Nordeste. Fig. 10B illustrates a more northerly position of the boundary between northerly and southerly wind components in the equatorial region. Furthermore, Fig. 8C exhibits weaker than average northerlies to the north, and stronger southerlies to the south of its boundary. The South Atlantic is marked by negative SST departures (Fig. 8D), and a major part of the North Atlantic by positive departures.

The conventional 5% fiducial limit is reached in a large area of negative SLP anomalies over the subtropical North Atlantic and a pocket of positive anomalies off the Angola coast in Fig. 8A. The results shown in Fig. 8A are quite different from those exhibited in Figs. 4A and 5A for the southern Nordeste. In Fig. 8B an area of strong easterlies appears on the northern Nordeste coast, departure being significant at the 5% level. The region of statistically significant weak easterlies over the North Atlantic is consistent with the weakened meridional pressure gradient illustrated by Fig. 8A. The strong southerlies to the south and weak northerlies to the north of the wind discontinuity (Fig. 8C) are also statistically significant. Finally, combining features revealed from Figs. 8B and 8C, it is noted that the enhanced southeast trades along the northern Nordeste coast are indeed statistically significant. The present analyses thus confirm the meteorologically significant findings of the earlier study by Hastenrath and Heller (1977), but enhance the results by establishing also the statistical significance of the prominent general circulation departure patterns.

During the wet years, SLP over the North Atlantic appears to increase (Fig. 9A). The map of zonal wind, Fig. 9B, indicates weak easterlies in the equatorial Atlantic. Consistent with the far southerly position of the boundary between northerly and southerly wind components (Fig. 10B), Fig. 9C shows weaker southerlies from the southern tip of the northern Nordeste to Ceará. A large pocket of warm water is observed in the South Atlantic (Fig. 9D), while negative SST departures prevail in the North Atlantic.

In Fig. 9A, the positive SLP anomalies along the northern coast of South America, embedded within the western portion of the equatorial trough of low pressure, are significant at the 5% level. An area of weakened easterlies along the Nordeste coast in Fig. 9B is statistically significant. However, departures of the meridional wind component are not statistically significant in this region. In confirmation of Hastenrath and Heller (1977) findings, the departure patterns during the wet are broadly inverse to the dry composite.

4. Case studies of recent extreme events

As described in Section 2, the period of surface wind observations over the Atlantic extends from

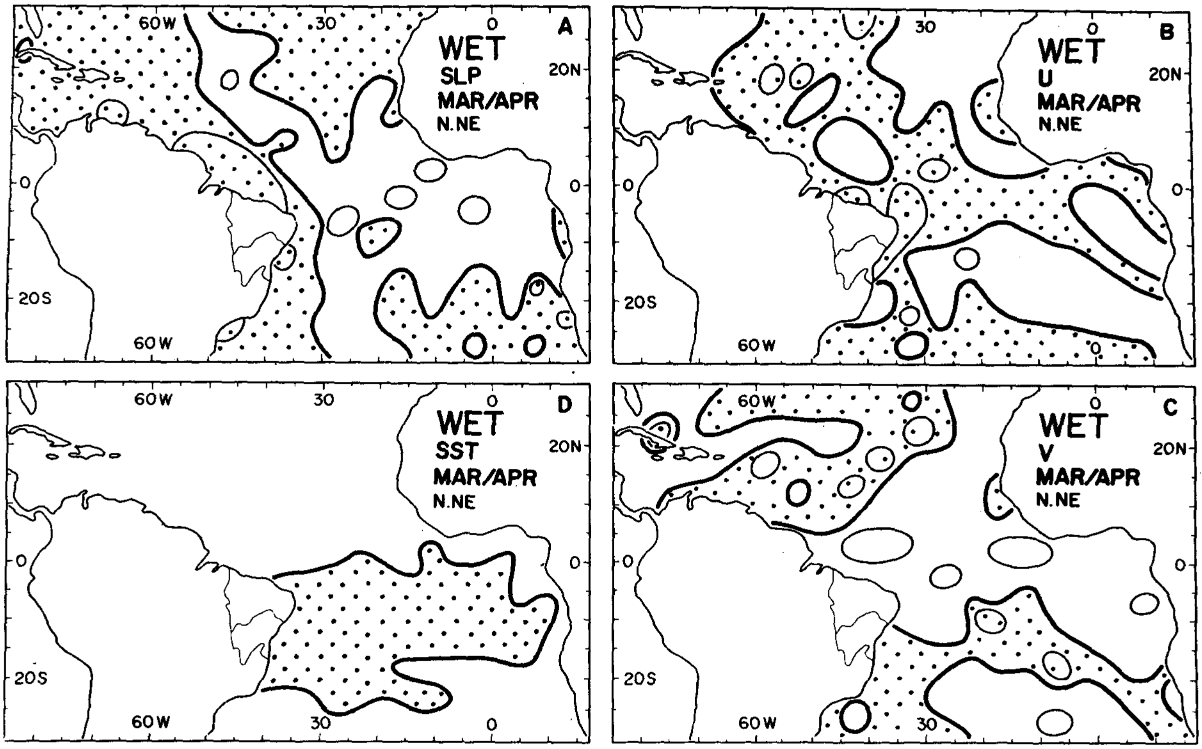

FIG. 9. March/April composite of ten extremely wet years (WET) in the northern Nordeste. Symbols as in Fig. 4.

1911–78, and monthly aerological records over South America are also available during 1968–78. These concurrent surface and upper-air data offer the opportunity to examine in detail the atmosphere–ocean behavior with respect to recent extreme events. This was precluded in the preceding for which solely 1911–72 ship records are available. The recent extreme years in the two regions are chosen as follows: 1975 as dry and 1977 as wet for the southern Nordeste; and 1970 as dry and 1974 as wet for the northern Nordeste.

For the analyses of upper-air circulation from the station network shown in Fig. 1, an objective analysis scheme (Madison Academic Computing Center, 1978) is used to interpolate values for grid points of a rectangular coordinate system. The scheme has a grid spacing of 5 degrees latitude and longitude, and boundaries of 10°N–30°S and 80°W–30°W. Thus the grid spacing is denser than the network in most of the map area, except over the Nordeste and subtropical Brazil.

Analyses are not presented in detail, as they broadly complement the results of the stratification studies discussed in Section 3. Only the upper-air circulation patterns during the March/April extremes of 1970 and 1974 for the northern Nordeste are displayed in Fig. 12, because of their relevance to the numerical model experiment of Moura and Shukla (1981). Reference is made to Chu and Hastenrath

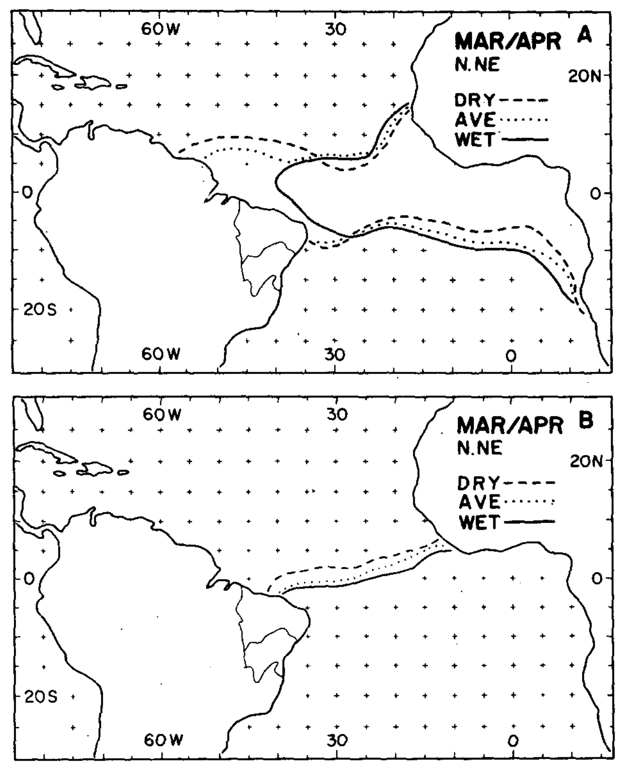

FIG. 10. March/April composite of the equatorial circulation components during extreme years in the northern Nordeste. Symbols as in Fig. 6.

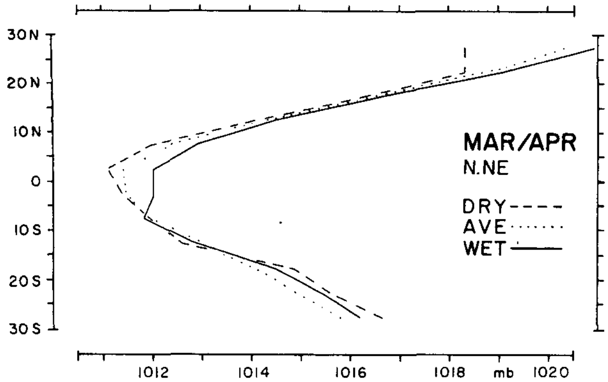

FIG. 11. March/April meridional profiles of sea-level pressure, zonally averaged for 25–55°W, during extreme years in the northern Nordeste. Symbols as in Fig. 7.

(1982) for a more extensive upper-air climatology over South America.

The low-level circulation during the dry March/April 1970 (Fig. 12B) is characterized by anticyclonic flow over eastern South America and strong southeast trades reaching more than 6 m s^{-1} over the northern Nordeste. At 200 mb, flow over the continent is predominantly westerly (Fig. 12A) in contrast to the mean circulations depicted in Chu and Hastenrath (1982).

For the wet March/April 1974, Fig. 12D shows that weak low-level northeast trades dominate over the interior of the Nordeste, unlike the occurrence of the southeast trades during the dry year (Fig. 12B). The most salient feature at 200 mb (Fig. 12C) is the northward flow over the Nordeste and equatorial North Atlantic.

A recent numerical experiment by Moura and Shukla (1981) using prescribed SST anomaly patterns such as illustrated in Figs. 8D and 9D, suggests a thermally direct meridional circulation, which during the northern Nordeste drought years would feature subsidence over northeast Brazil and ascending motion over the low-latitude North Atlantic, and southward/northward flow in the upper/lower layers. The inverse sense of departure configuration would correspond to the wet years in the northern Nordeste. The present case study (Fig. 12) shows for the very wet year 1974 a more southerly/northerly flow in the upper/lower troposphere than the moderately dry year 1970 (Fig. 2); the meridional circulation being more pronounced during the more extreme year 1974. The present study thus lends empirical support to the theoretical postulates of Moura and Shukla (1981).

5. Summary and conclusions

Departure patterns of indicative meteorological elements (SLP, *u*, *v*, and SST) over the tropical Atlantic were investigated for composites of extreme years in each region. Two-month ensembles repre-

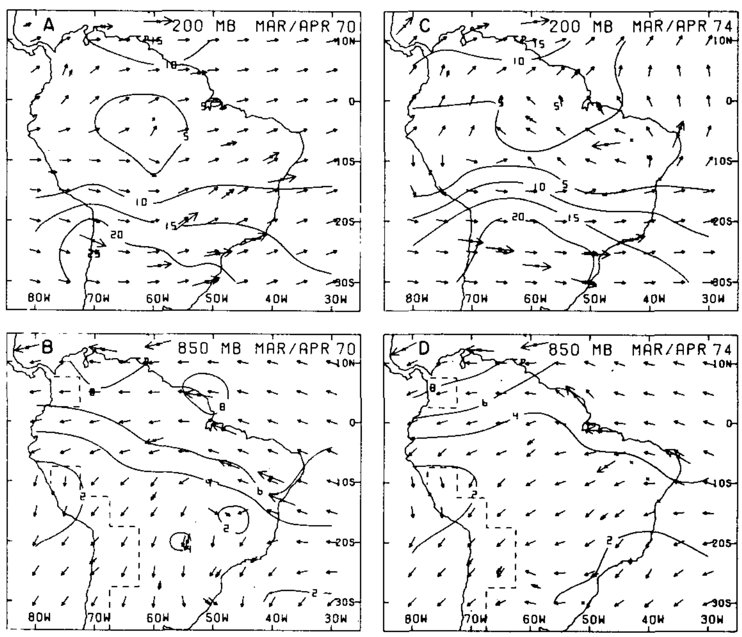

FIG. 12. March/April upper-air resultant winds over South America. Dashed lines indicate 5° squares with average surface topography above 1500 m (Berkofsky and Bertoni, 1955). Circulation of (A) 200 mb during dry year 1970; (B) 850 mb during dry year 1970; (C) 200 mb during wet year 1974; (D) 850 mb during wet year 1974.

sentative of the peak rainy season in each region were selected as follows: November/December for the southern Nordeste and March/April for the northern Nordeste.

The large-scale atmospheric circulation associated with drought years in the *southern Nordeste* is characterized by strong southeast trades to the north of the Bahia coast, and these onshore trades resemble the mean flow pattern during the dry season of interior Bahia (June–August). For years with abundant rainfall in the southern Nordeste, weak easterlies, a shift of meridional wind to a southerly direction, and anomalously cold water are observed along the east Brazilian coast. These phenomena may be related to Southern Hemisphere frontal systems which account for the maximum rainfall in November/December in the southern Nordeste. Departure patterns of large-scale atmospheric and oceanic fields may have meteorological importance, although conventional statistical fiducial limits are not reached.

Rainfall variations in the *northern Nordeste* are modulated by the varying morphology of the North and South Atlantic highs, the latitudinal displacement of the baric trough and enclosed confluence axis over the western equatorial Atlantic, and possibly by a meridional circulation cell induced by the juxtaposition of bands of positive and negative sea surface temperature anomalies. Rainfall activity may also be influenced by the effects of South Atlantic sea temperature on vapor flux and stability. The present study shows that the prominent and meteorologically significant departure patterns of atmospheric and oceanic fields characteristic of dry and wet years in the northern Nordeste are also statistically significant.

This mosaic of regional analyses indicates that the general circulation mechanisms of rainfall anomalies differ distinctly between neighboring areas. The climatic hazards of the northern Nordeste are clearly defined in terms of the large-scale circulation. The circulation features related to rainfall anomalies in the southern region are less distinct, and we have as yet reached only a very incomplete understanding of circulation mechanisms associated with the interannual rainfall variability in the southern Nordeste.

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