Diagnostic Studies of Brazil Climate: Preliminary Results

Contributions by
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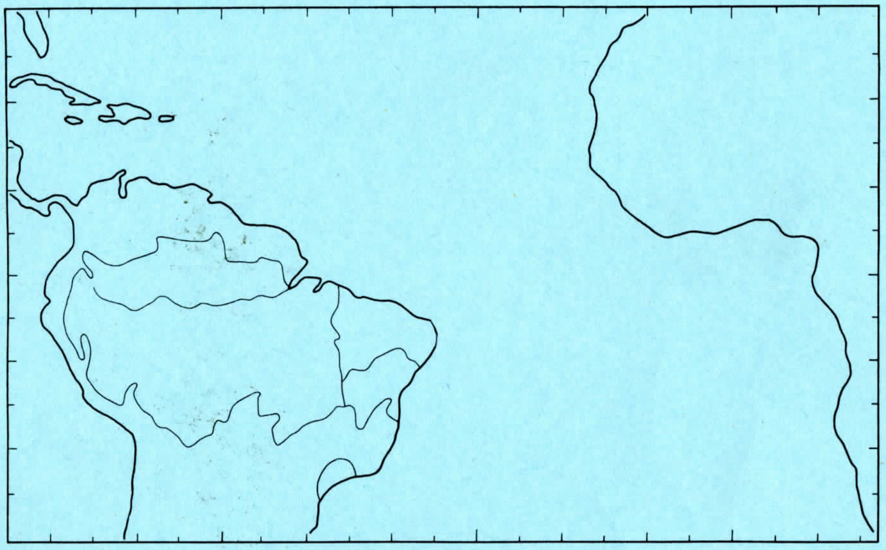

PROJECT REPORT

The research in this report has been supported by the Climate Analysis Center of the National Oceanic and Atmospheric Administration under Grant NA79AA-D-00131

March 1981

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Part I:

Summary of project activities

by Stefan Hastenrath

The project is focused on the climate diagnostics of the Brazil - tropical Atlantic sector, and developed from our work in the course of the past several years. Project tasks and preliminary research results during October 1979 - October 1980 are summarized in the following.

1. Background climatology

A reference climatology is basic to the diagnostic studies. The major components are: surface circulation over the tropical Atlantic; upper-air circulation over Brazil and adjacent parts of South America; hydrometeorology and regional water budget.

In addition to our atlases (Hastenrath and Lamb, 1977, 1978) that possess a one degree square spatial resolution, it was found desirable to have reference maps for the tropical Atlantic based on the same 5 degree blocks used in the subsequent diagnostic study of climate anomalies. Accordingly 60-year mean maps by calendar month were constructed for sea level pressure, zonal and meridional wind components, and sea surface temperature.

It is only in the course of the last ten years that a dense network of radiosonde stations has been operated over tropical Brazil. Accordingly it is now becoming possible to gain quantitative insight into the upper-air circulation over tropical South America. The greater part of the upper-air data has been placed on punch cards. This data processing effort shall form the basis for an updated aerological climatology.

A hydrometeorological background reference has been compiled in terms of rainfall index series, and river discharge series for large catchment areas. For the Amazon basin, an internally consistent water budget in terms of precipitation, evaporation, and runoff has been worked out.

2. Towards the monitoring and prediction of Northeast Brazil droughts

Our earlier diagnostic work (Hastenrath and Heller, 1977; Hastenrath, 1978; Covey and Hastenrath, 1978) indicates the importance of circulation anomalies over the tropical Atlantic for droughts in Northeast Brazil. With the aim of obtaining a possible predictor, the 1951-79 series of 700 mb contour maps published in the "Monthly Weather Review" was evaluated. In particular, index series of individual monthly height anomalies on the equatorward side of the North Atlantic high were constructed for this 30-year period. Monthly maps being obtained through courtesy of Dr. Donald Gilman allow an updating of this series. As seasonal foreshadowing on an operational basis will require long homogeneous reference series of predictors that are available on a timely basis, this parameter is an obvious choice. The Government of Brazil has taken an interest in our research and has invited collaboration in this task particularly.

3. Data archives

With a view towards later applications, some effort was invested in the reorganization and documentation of the data ensemble of long-term ship observations in the Atlantic. Monthly mean upper air data of stations in tropical Brazil that have accumulated over the past ten years are being placed on punch cards (section 1). Index series of 700 mb heights over the tropical North Atlantic are being kept up to date (section 2). Hydrometeorological index series have been compiled for various regions of Northeastern South America (section 1).

4. Diagnostics of extreme climatic events

Preliminary results of this research by Pao-Shin Chu are presented in section II.

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Part II:

Diagnostics of extreme climatic events

by Pao-Shin Chu

1. Introduction

The increased interest in the diagnostics of climatic fluctuations in the course of recent years reflects the important economic and social implications of climate variability (Federal Coordinating Council for Science, Engineering and Technology, 1977; National Academy of Science, 1977; National Oceanic and Atmospheric Administration, 1977; National Science Foundation, 1979, p. 33-34; World Meteorological Organization, 1980). A growing awareness of the role of climate variations in the national economy is shared by the Brazilian government, which is giving high priority to the task of combating drought in the region of Northeast Brazil (Fig. 1). In particular, the National Research Council of Brazil sponsored a workshop on climatic hazards in Northeast Brazil, held in São José dos Campos, São Paulo, Brazil, in February 1980. This had as central objectives the understanding of the dynamic causes of drought and the development of 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). More recently, the climate and circulation of tropical Brazil have been studied by Namias (1972), Markham (1974), Ratisbona (1975), Markham and McLain (1977), and Hastenrath and Heller (1977). Their results indicate that rainfall variations in the Nordeste are related to fluctuations in large-scale atmospheric and oceanic fields. Kousky and Chu (1978) pointed out the difference in the annual march of rainfall between the Southern and Northern portions of the Nordeste. They furthermore hypothesized that the circulation components involved in rainfall production differ between these two regions. Accordingly, analysis of large-scale circulation patterns over the contiguous tropical Atlantic is called for. By comparison with the early interest given to Brazil's

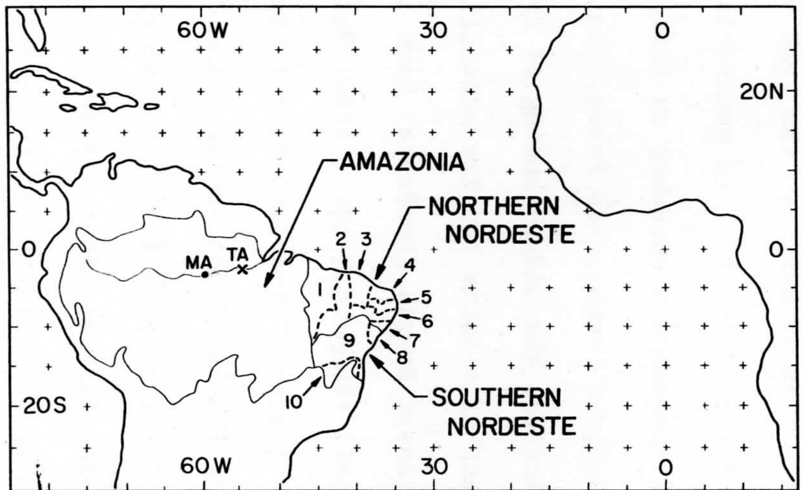

Fig. 1. Orientation map. The three large regions, Southern and Northern Nordeste, and Amazonia are delineated by solid boundaries. Water level gauging sites at Taperinha, TA, and Manaus, MA, are shown as cross and dot, respectively. States in the Nordeste are identified by numbers as follows: 1 Maranhão, 2 Piaui, 3 Ceará, 4 Rio Grande do Norte, 5 Paraiba, 6 Pernambuco, 7 Alagoas, 8 Sergipe, 9 Bahia, 10 Northern Minas Gerais.

Nordeste, little is known about the meteorology of the vast tropical lowlands of Amazonia. Water level records at Taperinha and Manaus (Fig. 1), along with rainfall data that have recently become available, offer the prospect of studying the climate and circulation of Amazonia. Although the three adjacent regions, Southern and Northern Nordeste and Amazonia, extend from the Atlantic coast to the foothills of the Andes through broadly the same latitude belt, their rainfall characteristics differ considerably.

Therefore, a mosaic of regional studies seems desirable, whereby the hydrometeorological anomalies in Southern and Northern Nordeste and in Amazonia are analyzed in relation to variations in the large-scale circulation. The following section 2 provides background information on hydrometeorological variability in the three large regions. Statistical tests are described in section 3. Analyses for the regions of Southern Nordeste, Northern Nordeste, and Amazonia are presented, respectively, in sections 4, 5 and 6. The objective of this study is to shed light on the causes of climate anomalies in tropical Brazil through analysis of prominent departure patterns in the large-scale circulation.

2. Interannual variability of rainfall

The major hydrometeorological reference is provided by the series depicted in Fig. 2. For the Southern Nordeste, monthly rainfall totals of 40 stations during 1912-1972 were obtained from Superintendencia do Desenvolvimento do Nordeste (1969, 1977). Processing is patterned after Hastenrath and Heller (1977). In accordance with the November-January rainy season, data were seasonalized for the period July to June. The resulting 12-month sums are ascribed

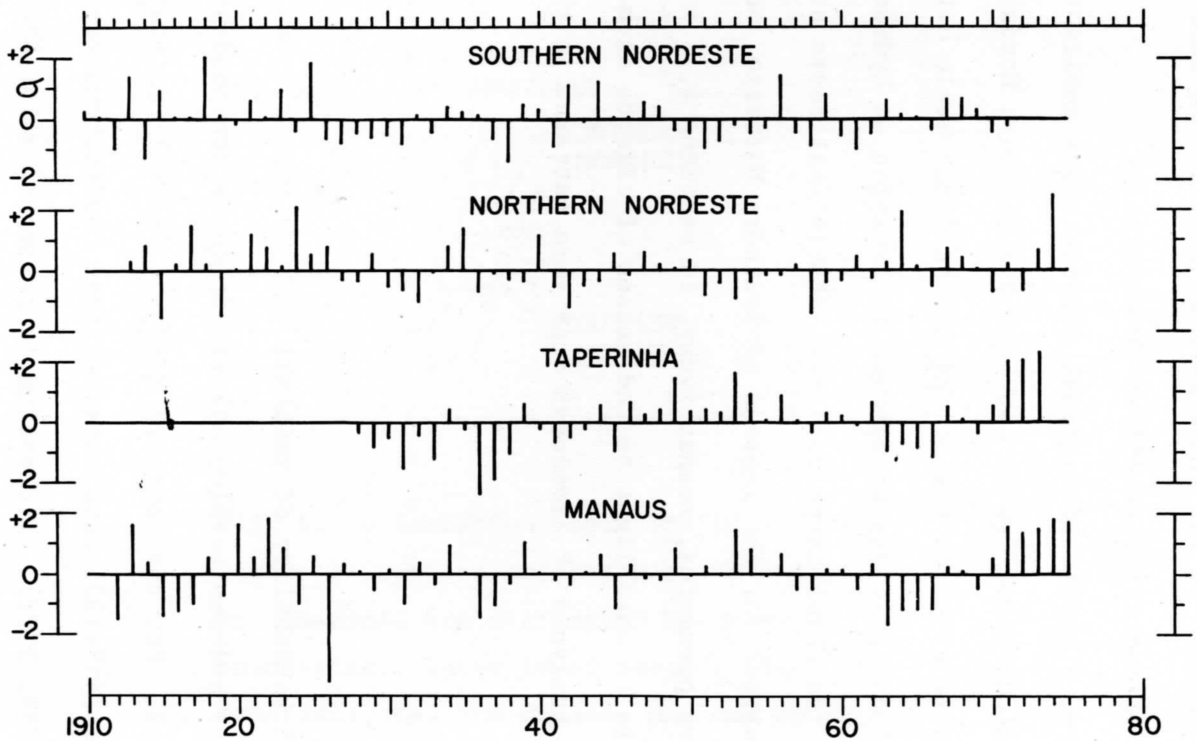

Fig. 2. All-station average of normalized departure of annual rainfall for the Southern and Northern Nordeste, and normalized departure of annual water levels at Taperinha, Amazon, and Manaus, Rio Negro.

to the earlier calendar year. Departures of individual seasonalized annual rainfall totals from the mean are expressed in terms of standard deviation. These normalized departures are subsequently averaged over the 40 stations to yield a regional rainfall index, R. For the Northern Nordeste, the rainfall index series constructed by Hastenrath and Heller (1977) from a network of 40 stations is used. For the series of Amazon water level at Taperinha (1928-1973) and Manaus (1912-1975), calendar-year departures were expressed in terms of standard deviation.

From the rainfall index series for the Southern Nordeste, extreme years are identified as follow: 19<u>12</u>, <u>14</u>, 27, 31, <u>38</u>, 41, 51, 52, <u>58</u>, 61, as dry; and 19<u>13</u>, 15, <u>18</u>, 23, <u>25</u>, 42, 44, <u>56</u>, 59, 68, as wet; underlined years being very extreme. For all ten dry years R is less than -0.8 σ and for the ten wet years it is greater than +0.7 σ. For the Northern Nordeste, Hastenrath and Heller (1977) identified extreme years as follow: 19<u>15</u>, <u>19</u>, 30, 31, 32, 36, <u>42</u>, 51, 53, and <u>58</u>, as dry; and 19<u>17</u>, 21, 22, <u>24</u>, 26, 34, <u>35</u>, 40, <u>64</u>, and 67, as wet; underlined years being very extreme. For all ten dry years R is -0.5 σ or beyond, and for the ten wet years it is equal to or larger than +0.7 σ. For Amazonia, the ten years with extremely low water level are 1929, <u>31</u>, 33, <u>36</u>, <u>37</u>, 38, 45, 63, 65, 66; and the ten years with extremely high water level 1939, 46, 49, 53, 54, 56, 62, <u>71</u>, <u>72</u>, <u>73</u>; underlined years being very extreme. For the former collective, water levels are beyond -0.9 σ and for the latter they exceed +0.6 σ.

For composites of the ten driest and ten wettest years as identified for the three regions, departure maps of meteorological elements over the Atlantic were constructed. Departure maps of these elements are subjected to testing for statistical significance.

3. Statistical test

The t-test is used to compare the means of pairs of samples. The one sample is made up of the ten driest or ten wettest years, and the other, reference sample, consists of all years excluding the extreme years. The t-test is based on the premise that two samples are (a) independently drawn from the population, (b) that they both possess normal distribution, and (c) that they have common variance. These premises must be verified before application of the t-test.

(a) In order to ascertain independence of data, 12 five-degree blocks are chosen for which series of sea level pressure (SLP), zonal (u) and meridional (v) wind components and sea surface temperature (SST) are examined (Fig. 3). Autocorrelation coefficients are computed as defined by

$$\gamma_L = \frac{\sum_i (X_i - \bar{X})(X_{i+L} - \bar{X})}{\sigma_x^2 N}$$

where L is the lag and σ_x^2 the variance. Commensurate with the typical length of record of about 60 years, L is here set to 10.

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.

(b) Normality of data is examined from histograms which are generated by MINITAB graphical package (Ryan et al., 1976). The distributions of SLP, u, v and SST are found to be approximately normal.

(c) For comparing the variance of two normal distributions, the idea of F-distribution for testing the hypothesis of common variance is applied. Hypotheses are tested at a specified significance level α_o

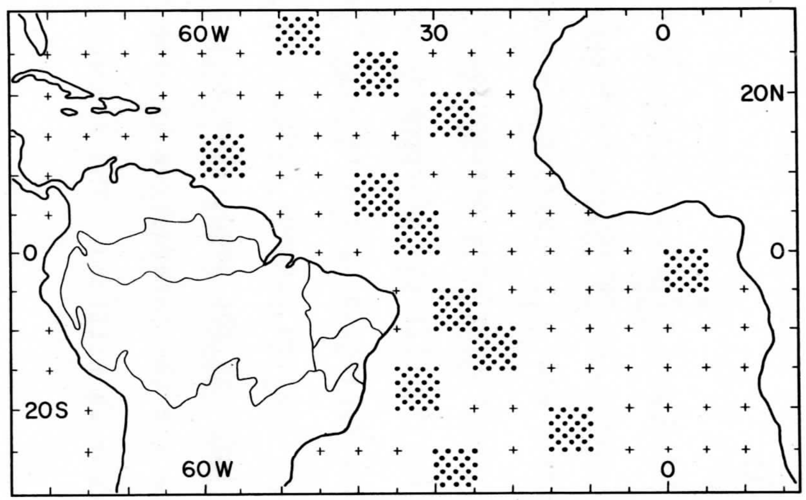

Fig. 3. Dot raster indicates five-degree blocks for which statistical testing was performed.

$$H_o : \sigma^2_{ext} = \sigma^2_{ref}$$

$$H_1 : \sigma^2_{ext} \neq \sigma^2_{ref}$$

where H_o is the null hypothesis and H_1 the alternative hypothesis; the variance σ^2_{ext} is unknown from the sample of extreme years $X_1, \ldots, X_m$, and σ^2_{ref} is also unknown from the sample of reference years $Y_1, \ldots, Y_n$. The statistic V is defined as (DeGroot, 1975)

$$V = \frac{S^2_{ext}/(m-1)}{S^2_{ref}/(n-1)}$$

where $S^2_{ext} = \sum_{i=1}^{m} (X_i - \bar{X}_m)^2$ and $S^2_{ref} = \sum_{i=1}^{n} (Y_i - \bar{Y}_n)^2$. It is desired to reject H_o if either $V < C_1$ or $V > C_2$, where the constants C_1 and C_2 are chosen so that when H_o is true, the probability $Pr(V<C_1) = Pr(V>C_2) = 0.025$. 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 (a), only the series of SLP, u and v are subjected to the t-test. One null hypothesis (H_o) is that the mean value of a given element during the composite of reference years (μ_{ref}) is at least as large as the mean value during the extreme years (μ_{ext}). The opposite is true for the laternative hypothesis (H_1); in this case, the so-called 'one-tailed' test is utilized. The aforementioned hypotheses can be expressed as

$$H_o : \mu_{ext} \leq \mu_{ref}$$

$$H_1 : \mu_{ext} > \mu_{ref}$$

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

$$U = \frac{(m+n-2)^{\frac{1}{2}} (\bar{X}_m - \bar{Y}_n)}{(\frac{1}{m} + \frac{1}{n})^{\frac{1}{2}} (S_{ext} + S_{ref})^{\frac{1}{2}}}$$

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. Since the ship data are available during the period 1911-1972, ideally m would be 20 and n 84 for the two-month ensembles used to represent the peak rainy season in each season. The $\bar{X}_m$ and $\bar{Y}_n$ are, respectively, the average of all individual monthly values available from the two-month ensembles for the set of extreme years, and the set of reference years. Using two different calendar months in each ensemble has the advantage of enlarging the sample, although the variance is being contributed to by the annual march. Thus, the test tends to underestimate the significance of departure patterns. According to the likelihood ratio test, the null hypothesis (H_o) should be rejected if $U \geq c$ and be accepted if $U < c$, where c is the table value corresponding to $m + n - 2$ degrees of freedom. Similarly, H_1 should be rejected if $U < c$, and accepted if $U \geq c$. In this study, 20 percent and 5 percent levels of significance are chosen.

The following example may illustrate the application of this test. Consider that for SLP in some oceanic region the null hypothesis $H_o : \mu_{ext} \leq \mu_{ref}$ is rejected at the 5 percent significance level. This is interpreted as the mean SLP during the extreme years being significantly larger than the mean SLP during the reference years, at the 5 percent level.

4. 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 sea level pressure (SLP), zonal (u) and meridional (v) wind components and sea surface temperature (SST). 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 W - 55 W.

4.1 DRY composite

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 departures elsewhere.

For the DRY composite, a t-test is applied to the fields of SLP, u and v. In Fig. 4A, SLP in a large area adjacent to the Southern Nordeste significantly exceeds the mean of the reference years, in that the null hypothesis $H_o : \mu_{ext} \leq \mu_{ref}$ is rejected at the 20 percent significance level. Similarly, the negative pressure departure along the northern coast of South America is significant at the 20 percent level. In Fig. 4B, easterly flow along the coast of Brazil is found to be significantly stronger than during the reference years, this departure being significant at the 20 percent level. In Fig. 4C, the positive departures of the southerly component along the Northern Nordeste coast is shown to be significant at the 5 percent level.

4.2 WET composite

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.

In Fig. 5B, easterlies appear weakened over the western South and most of the North Atlantic, but strengthened along the South Brazilian coast.

Fig. 5C displays weakened northerlies along the East Brazilian coast and strengthened southerlies on the South Brazilian coast.

The SST map, Fig. 5D, indicates anomalously warm waters in the equatorial Atlantic.

The negative SLP departure over the South Atlantic in Fig. 5A is found by the t-test to be statistically significant at the 20 percent level. Similarly, the weakened easterlies along the Brazilian coast in Fig. 5B and the enhanced southerlies along the South Brazilian coast in Fig. 5C correspond to isopleths of 20 percent significance.

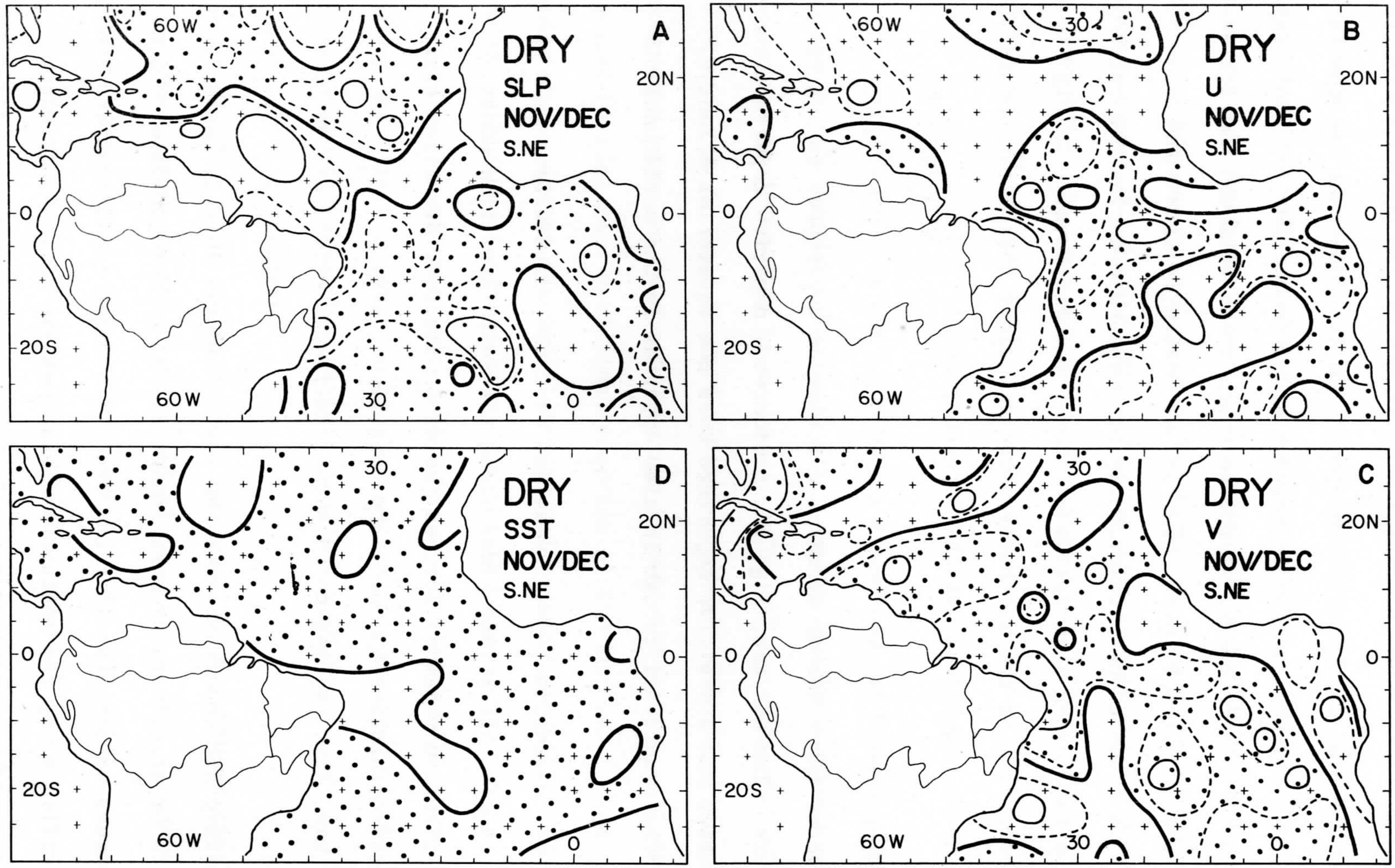

Fig. 4. November/December composite of the ten extremely dry years (DRY) in the Southern Nordeste expressed as departure from the 60 year mean. (A) sea level pressure, (B) zonal wind component, (C) meridional wind component, and (D) sea surface temperature. Positive areas are shaded with heavy solid line denoting zero departure. Thin broken and solid lines refer to the 20 and 5 percent significance levels, respectively.

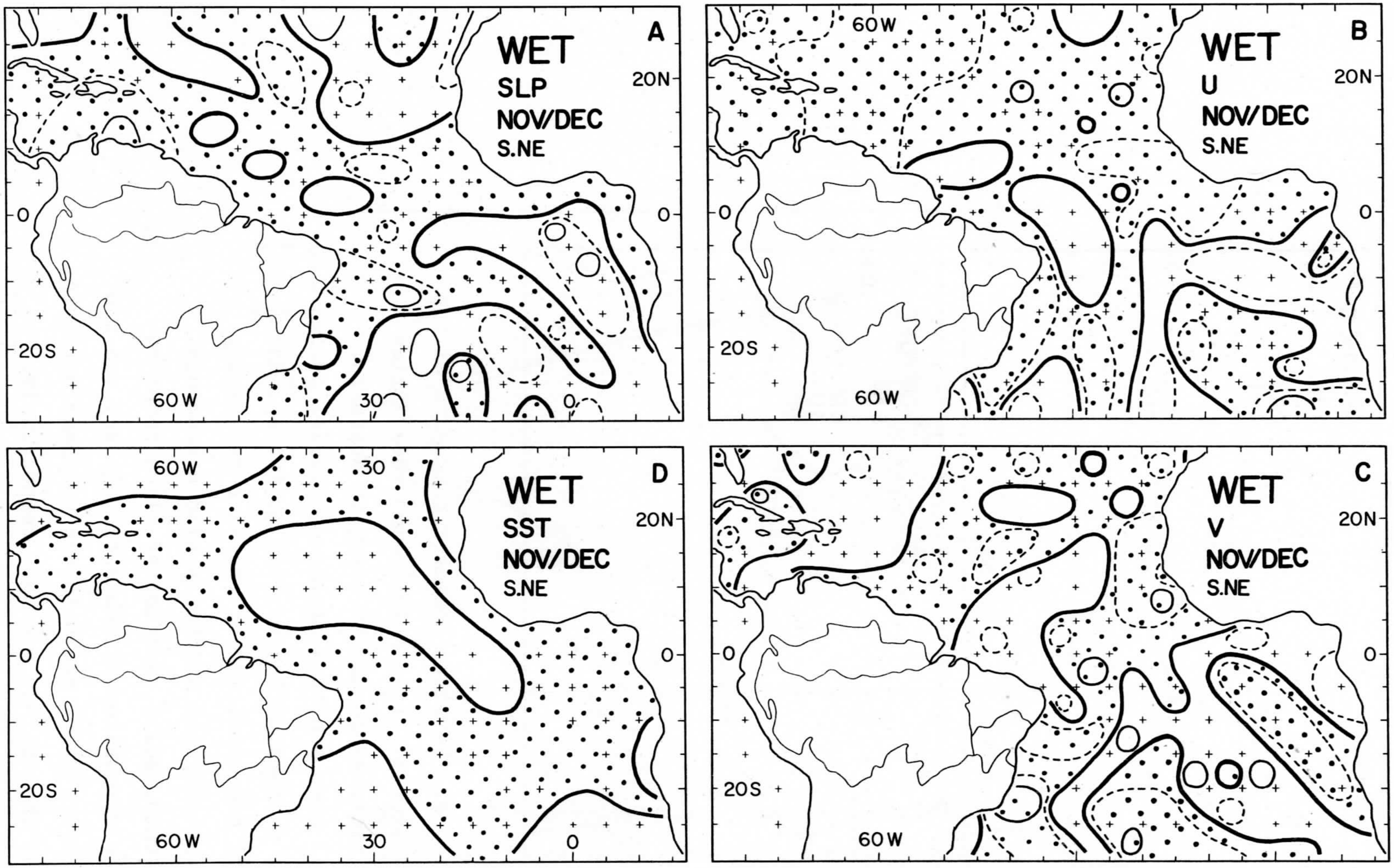

Fig. 5. November/December composite of ten extremely wet years (WET) in the Southern Nordeste. Symbols are as in Fig. 4.

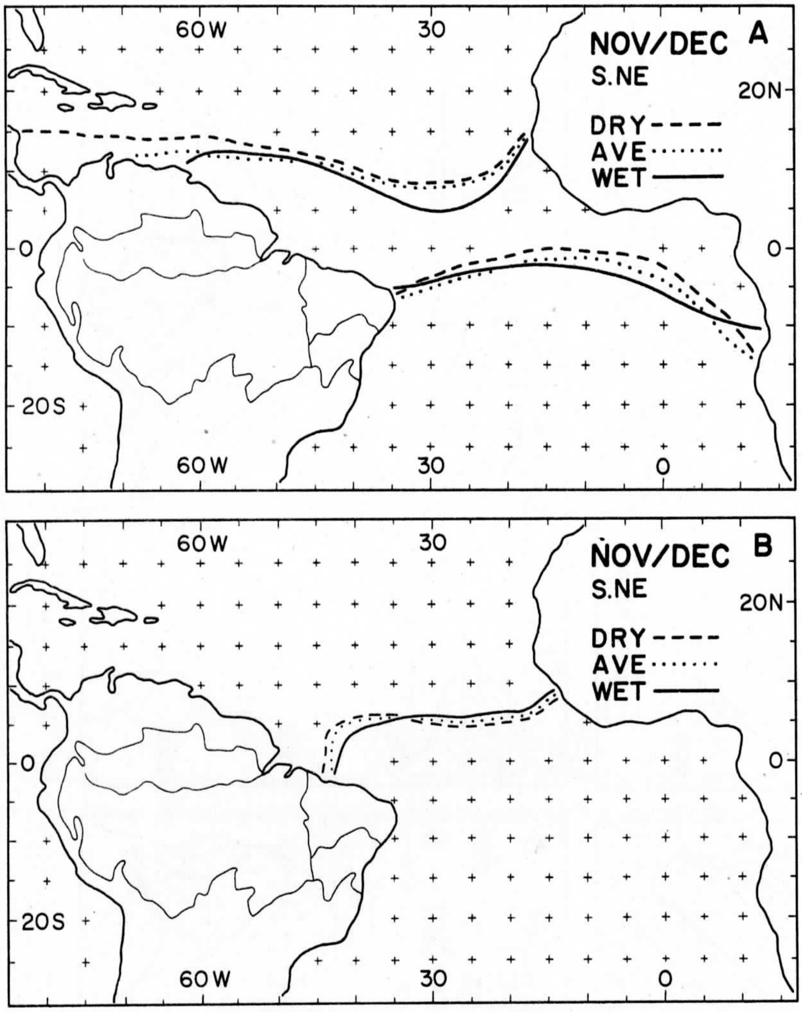

Fig. 6. November/December composite of the equatorial circulation components during extreme years in the Southern Nordeste. (A) mean position of the equatorial trough as delineated by the 1012 mb isobar, and (B) mean position of the line separating southerly and northerly wind components. Broken, solid, 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.

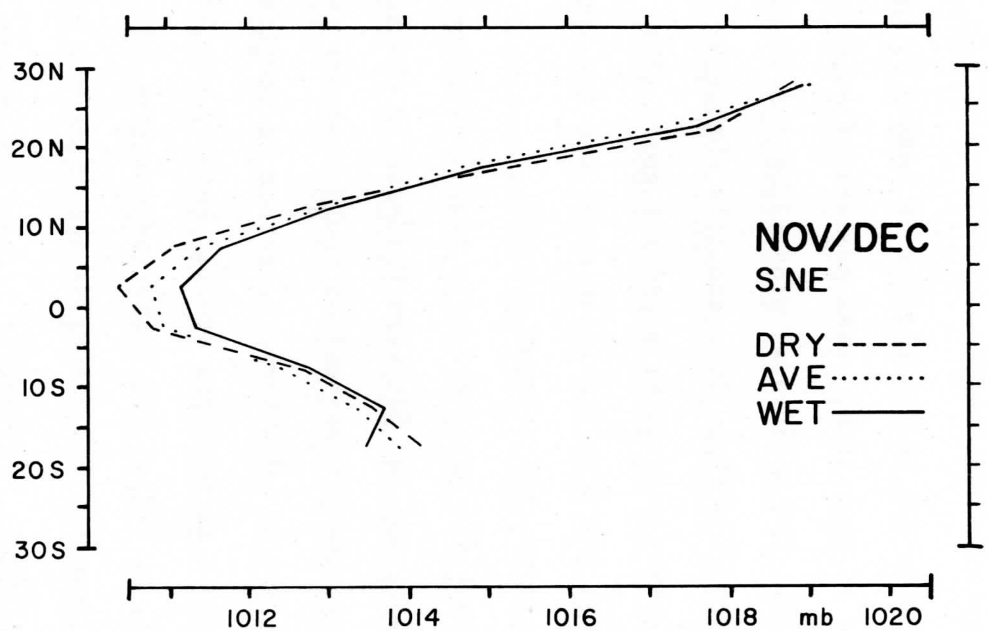

Fig. 7. November/December composite meridional profiles of sea level pressure, zonally averaged for 25 W - 55 W, during extreme years in the Southern Nordeste. Broken, solid, and dotted lines refer to the composites of ten extremely dry and ten extremely wet years in the Southern Nordeste, and the 1911-1970 average, respectively.

4.3 Synopsis

Kousky and Chu (1978) have suggested that much of the precipitation in interior Bahia is associated with frontal systems. More recently, Kousky (1979) analyzed surface continental records for a ten-year period and noted that frontal activity may account for the maximum rainfall in November/December in the Southern Nordeste. Based on long-term ship observations, the present analysis attempts to explore the extreme rainfall behavior in Bahia in relation to atmospheric conditions over the ocean.

During the wet years, the South Atlantic is marked by negative pressure departures (Fig. 5A), and at such times 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 temperature contrast along the East Brazilian coast and the appearance of southerlies may be associated with frontal systems.

During the dry years the South Atlantic high is stronger than in the sixty years mean (Fig. 4A), and the Southern Nordeste is characterized by strong easterlies. These strong on-shore easterlies 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, 1975, 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).

5. 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: (a) Their analysis based on data by one degree square areas is repeated with a five-degree square resolution, so as to facilitate comparison with other regional investigations in the present study. (b) Expanding on their study, departure patterns are subjected to statistical testing.

5.1. DRY composite

Fig. 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 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 this boundary. The South Atlantic is characterized by negative SST departures (Fig. 8D), and a major part of the North Atlantic by positive departures.

The negative SLP anomalies over the North Atlantic in Fig. 8A are significant at the 20 percent level. In Fig. 8B, an extensive area of strong easterlies appears on the Northern Nordeste coast, departure being significant at the 5 percent level. The strong southerlies to the south and weak northerlies to the north of the boundary between northerly and southerly wind components (Fig. 8C) correspond to isopleths of 5 percent significance.

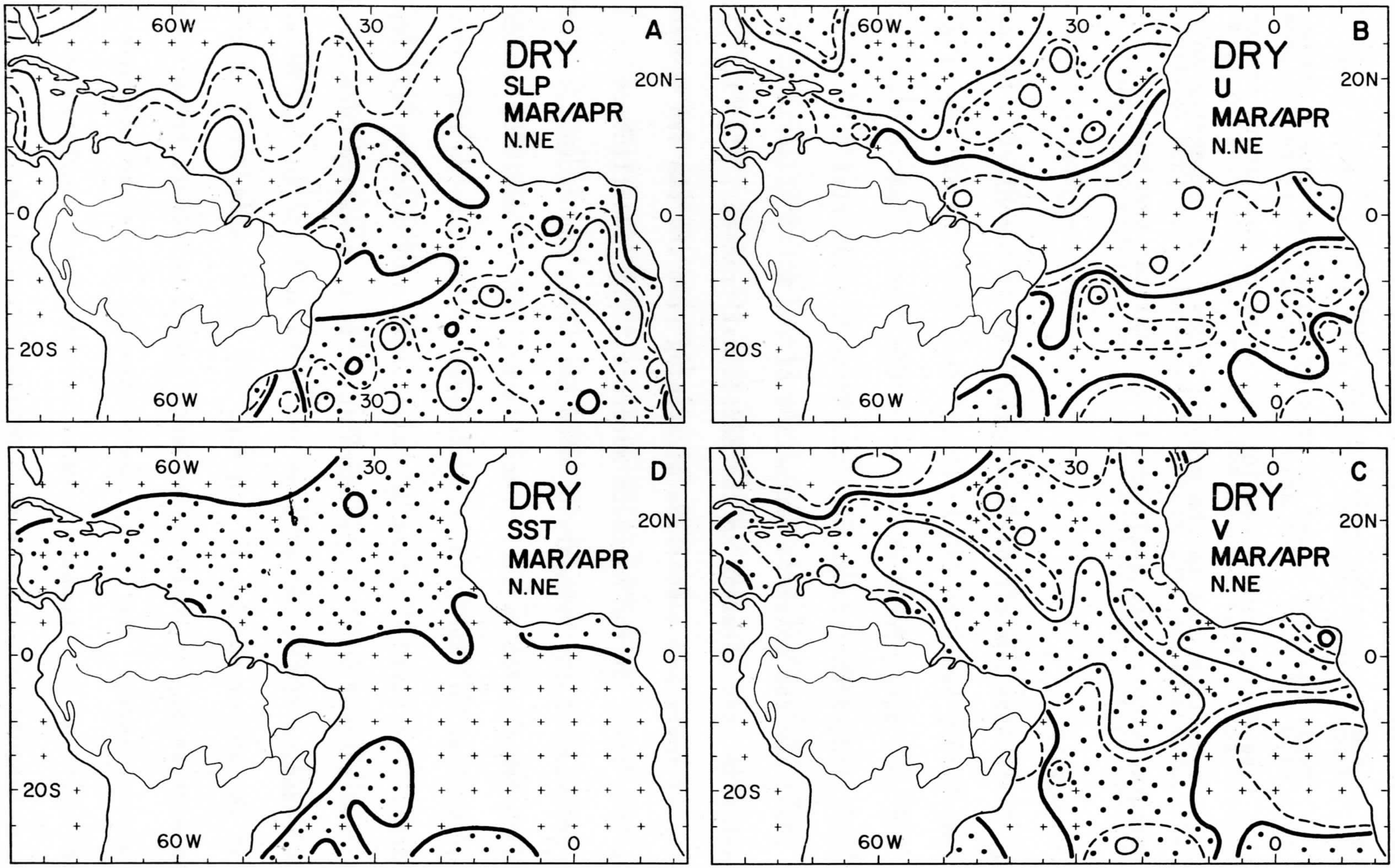

Fig. 8. March/April composite of ten extremely dry years (DRY) in the Northern Nordeste. Symbols are as in Fig. 4.

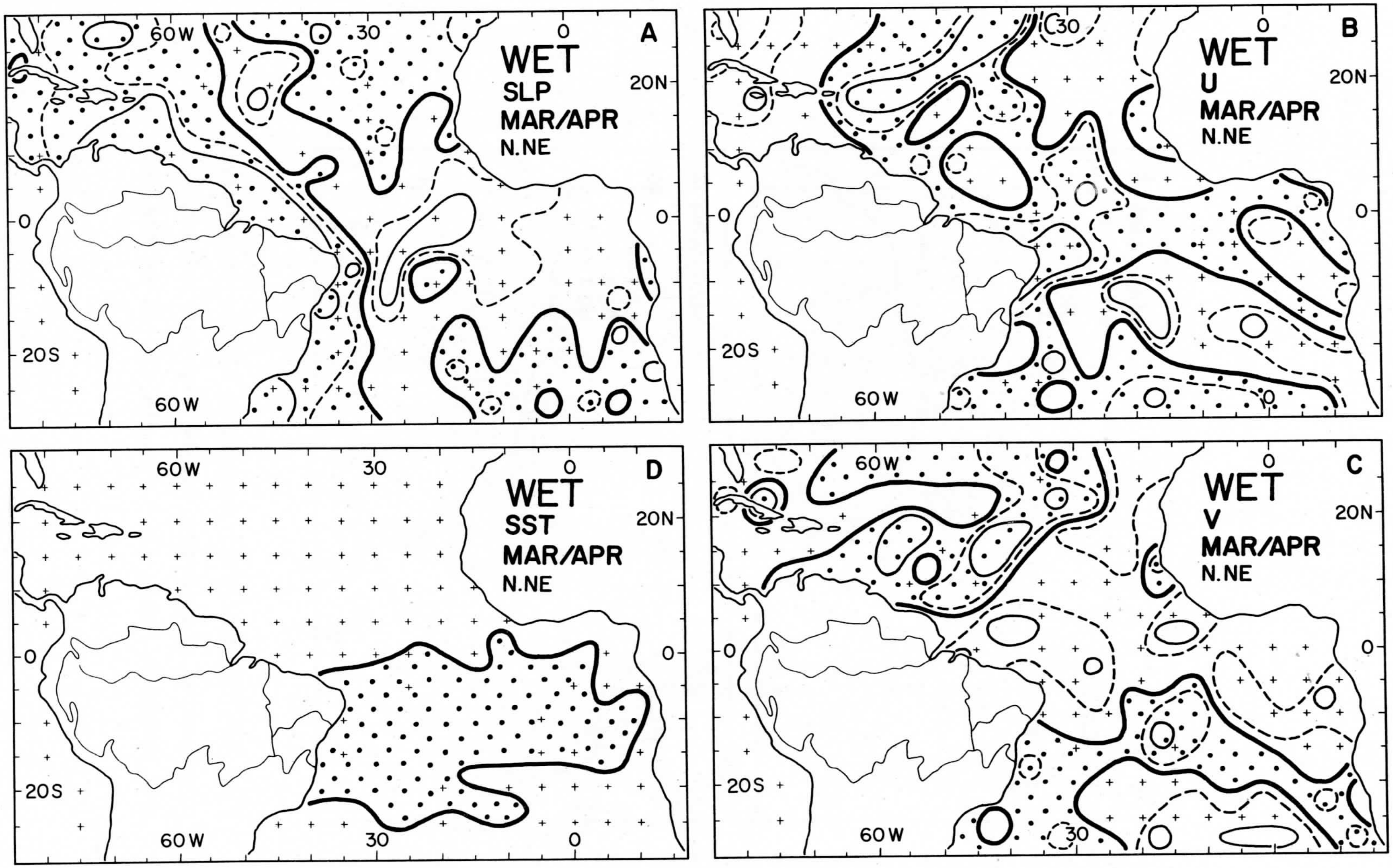

Fig. 9. March/April composite of ten extremely wet years (WET) in the Northern Nordeste. Symbols are as in Fig. 4.

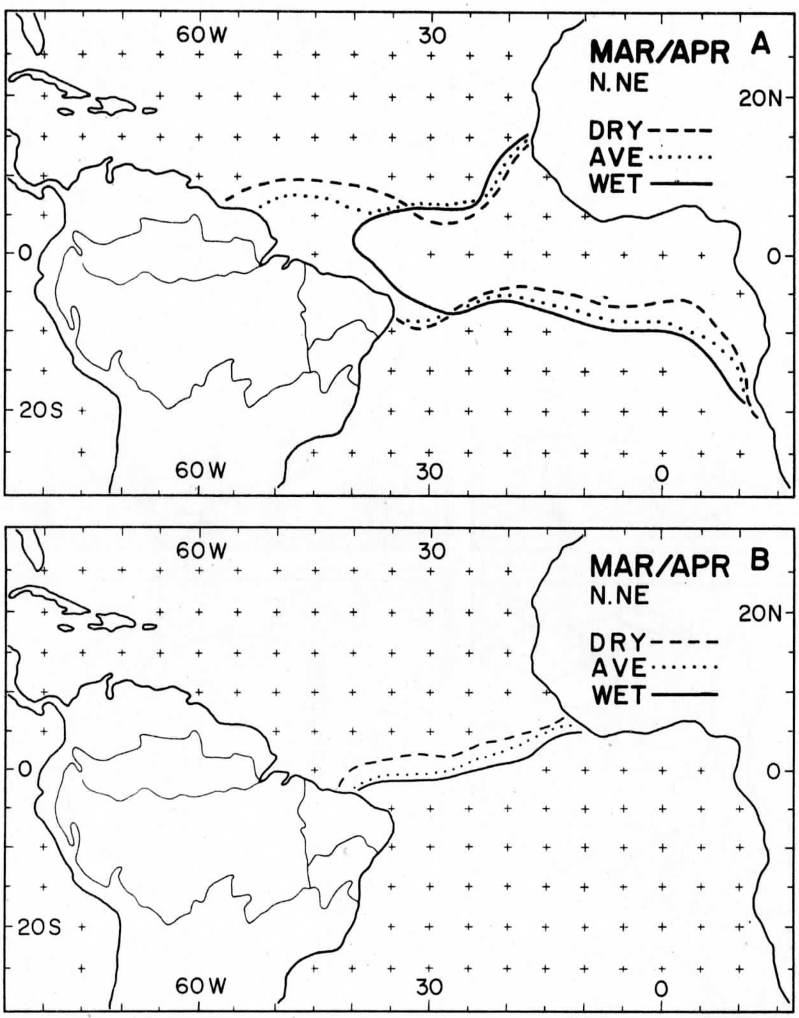

Fig. 10. March/April composite of the equatorial circulation components during extreme years in the Northern Nordeste. Symbols are as in Fig. 6.

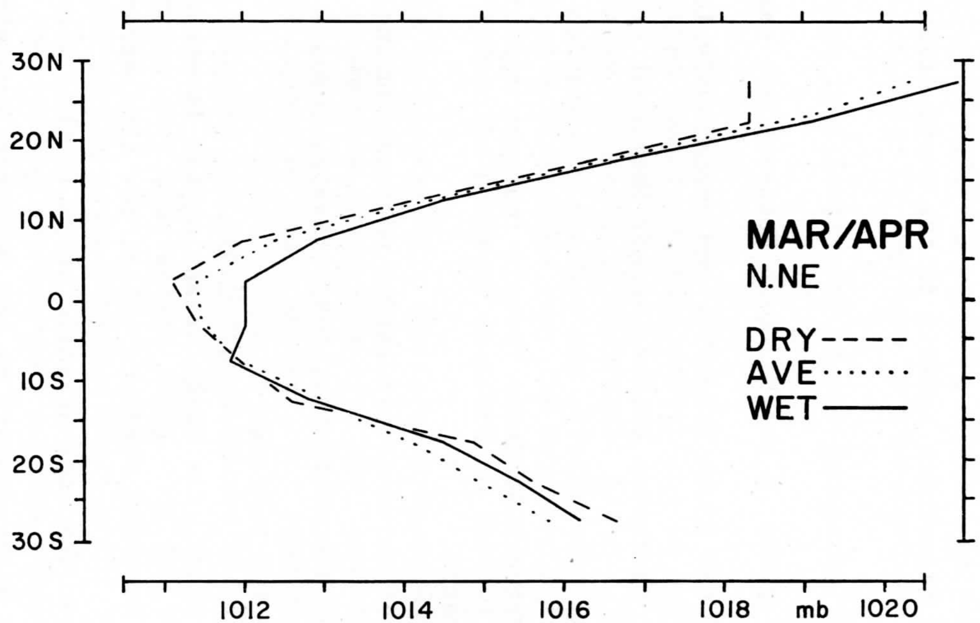

Fig. 11. March/April meridional profiles of sea level pressure, zonally averaged for 25 W - 55 W, during extreme years in the Northern Nordeste. Symbols are as in Fig. 7.

5.2 WET composite

During the wet years, SLP on the equatorward side of the South Atlantic high is reduced (Fig. 9A). The map of zonal wind, Fig. 9B, indicates weakened easterlies in the equatorial Atlantic. Consistent with the far northerly position of the boundary between northerly and southerly wind components (Fig. 10B), Fig. 9C shows weaker southerlies from the southern tip of 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.

5.3 Synopsis

The drought years in the Northern Nordeste are characterized by positive SLP anomalies over the South Atlantic, and anomalously low SLP over the North Atlantic, stronger Southeast trades, weaker Northeast trades and cold water in the South Atlantic. Conversely, the surface circulation during years of abundant rainfall in the Northern Nordeste reveals features approximately opposite to those during dry years.

Comparison of surface circulation patterns during the peak rainy seasons of Southern and Northern Nordeste, respectively, reveals the following features common between the two regions:

a. During the dry years, the South Atlantic high is strong, enhanced easterlies prevail along the Northern Nordeste coast, the line separating the northerlies and southerlies over the West Atlantic stays further westward than the mean position, and cold water appears on the Northern Nordeste coast.

b. During the wet years, the equatorial easterlies weaken, the line separating the northerlies and southerlies stays further eastward and warm water shows on the Nordeste coast.

The features which differ between the two regions are as follows:

a. Anomalously low pressure over the North Atlantic is characteristic of dry years in the Northern Nordeste, but not the Southern Nordeste.

b. The displacement of the boundary between northerlies and southerlies is more pronounced for extreme events in the Northern Nordeste than in the Southern Nordeste (Figs. 6B and 10B); thus the meridional displacement of this boundary seems to exert minimal influence on extreme rainfall events in the Southern Nordeste.

6. Amazonia

Due to the paucity of rainfall stations in the vast Amazon basin, water level series at Taperinha (Fig. 1) are used to represent the upstream hydrometeorological conditions in a large part of the Amazon basin.

6.1 DRY composite

Fig. 12 illustrates the circulation departures in April/May for the composite of ten extremely dry years in the Amazon basin. The SLP map, Fig. 12A, exhibits negative departures over the North Atlantic. The meridional SLP profile, Fig. 15, shows the pressure gradient to the North of the Equator during the dry years to be slacker than the long-term average. The map of zonal wind, Fig. 12B, shows weak easterlies over the equatorial Atlantic, especially along the North coast of South America, but enhanced easterlies over the subtropical North Atlantic and along the southeast Brazilian coast. Fig. 12C indicates weak northerlies over the eastern portion of the North Atlantic and weak southerlies in part of the equatorial South Atlantic. This is consistent with a more northerly position of the boundary between northerlies and southerlies, illustrated by Fig. 14B. Positive SST anomalies prevail in the equatorial Atlantic (Fig. 12D).

The negative pressure departures along the North coast of South America (Fig. 12A) correspond to isopleths of 20 percent significance. Off the North coast of South America, the weakening of easterlies and northerlies is significant at the 20 percent level (Figs. 12B and 12C).

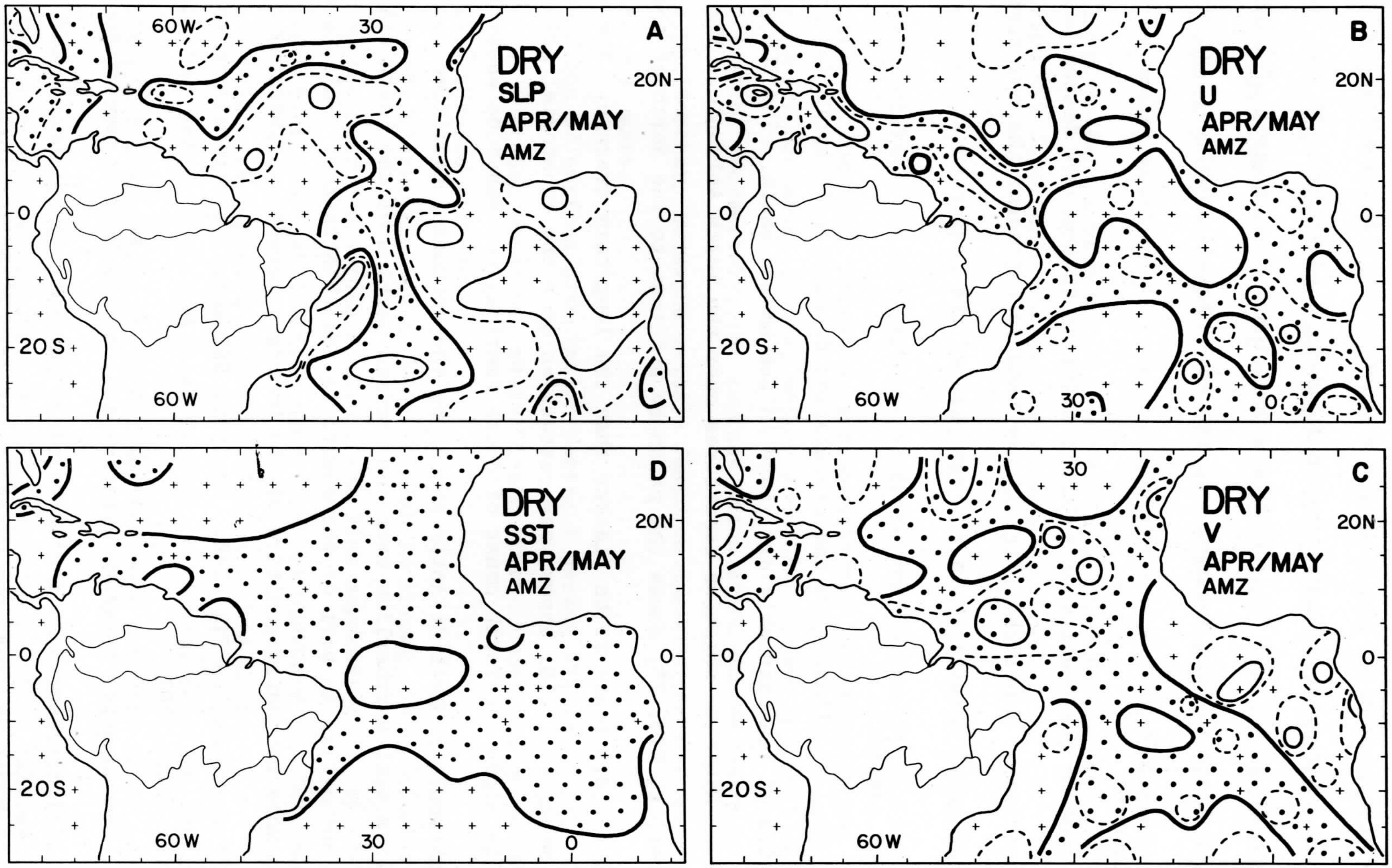

Fig. 12. April/May composite of ten extremely dry years (DRY) in Amazonia. Symbols are as in Fig. 4.

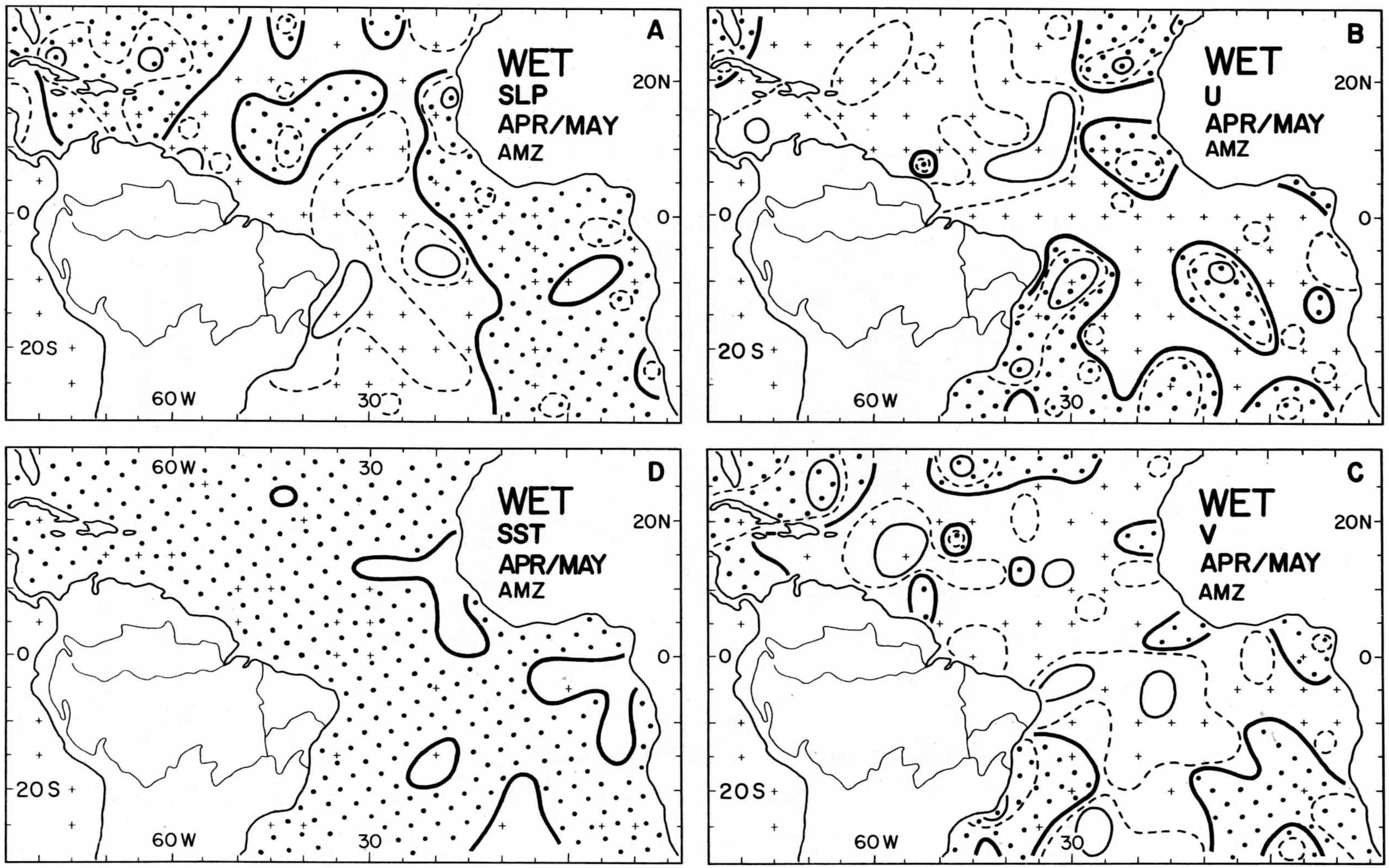

Fig. 13. April/May composite of ten extremely wet years (WET) in Amazonia. Symbols are as in Fig. 4.

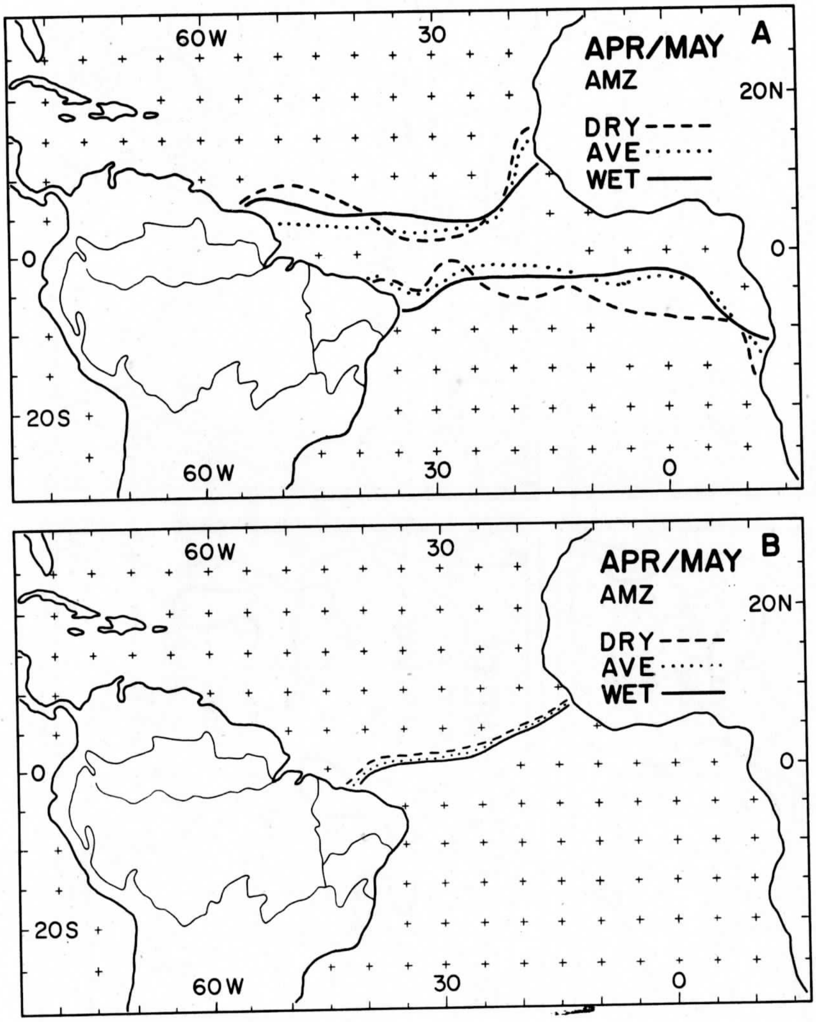

Fig. 14. April/May composite of the equatorial circulation components during extreme years in Amazonia. Symbols are as in Fig. 6.

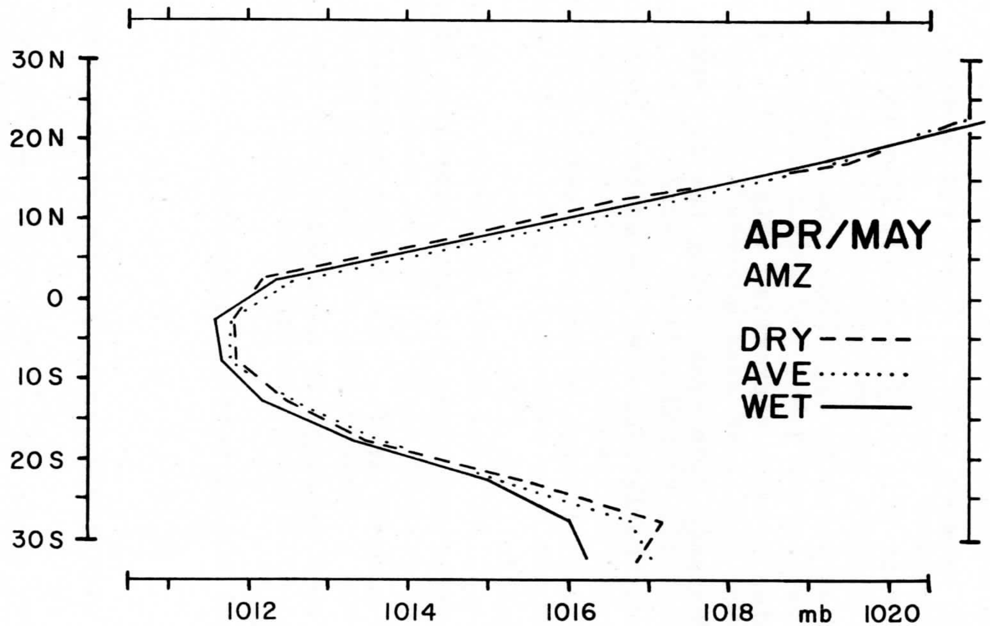

Fig. 15. April/May meridional profiles of sea level pressure, zonally averaged for 25 W - 55 W, during extreme years in Amazonia. Symbols are as in Fig. 7.

6.2 WET composite

Fig. 13A shows negative pressure departures extending from the Guyana coast eastward to about 25 W. As illustrated in Fig. 14A, the equatorial trough is broader and deeper than in the long-term average. Consistent with the map, Fig. 14A, the meridional SLP profile, Fig. 15, also exhibits a deeper trough to the South of the Equator, while at latitudes 30 - 15 N, SLP differs little from the long-term average. Accordingly, the meridional pressure gradient appears steepest between about 15 N and the Equator. Consistent with the steeper pressure gradient (Fig. 15), easterly flow is enhanced over a large portion of the Atlantic, as shown in Fig. 13B. The area off the Southeast Brazilian coast is occupied by weak easterlies (Fig. 13B). It is recalled that strong easterlies dominate this area during the dry years (Fig. 12B). Fig. 13C depicts strong northerly flow over the eastern North Atlantic and weak southerlies in the central South Atlantic. Positive SST departures occupy most of the tropical Atlantic (Fig. 13D).

The negative SLP departure along the East Brazilian coast in Fig. 13A is significant at the 20 percent level. The strong easterlies and northerlies off the North coast of South America are associated with the 20 percent isopleths (Figs. 13B and C).

6.3 Synopsis

During the years with low water level, the near-equatorial trough of low pressure is less developed (Fig. 14A), the meridional pressure gradient on its northward side is slack (Fig. 15), and the North Atlantic trades are weak (Figs. 13B and C). By contrast, during the high water level years, the near-equatorial trough is deeper (Fig. 14A), the meridional SLP gradient to the North is steep (Fig. 15), and the Northeast trades are enhanced (Figs. 13B and C). It is surmised that strengthened Northeast trades may entail increased water vapor transport into the basin. Lettau et al. (1979) offered a similar conjecture based on Newell et al.'s, (1972) charts. Further analysis shall verify the validity of this argument.

Concomitant with the deep equatorial trough and strengthened Northeast trades during wet years in Amazonia, the western South Atlantic experiences lower SLP, weaker easterlies and stronger southerlies than in the long-term mean (Figs. 14A, 13A, B and C). The strength of the North Atlantic trades may be a factor for the moisture import into the Amazon basin. Also, the deepening of the equatorial trough over the Atlantic during wet years may be indicative of conditions over the adjacent continent, the deepened trough probably being related to enhanced convective activity. The lower SLP over the western South Atlantic during wet years may reflect increased occurrence of large synoptic systems along the East Brazilian coast. In his study of frontal influences on Northeast Brazil, Kousky (1979) describes nearly simultaneous pressure variations spanning an area from the coast of Bahia to the upper Amazon basin (∿70 W). Such a pressure coupling may be related to the deep intrusion of the upper-level trough into the tropics as noted by Riehl (1977) in his investigation of the rainfall systems in Venezuela. When the upper-level trough extends far into low latitudes, the surface pressure would be correspondingly low. The interaction of the ITCZ and frontal activity in Southern Brazil in March is clearly depicted in the satellite image of Kousky (1979).

7. Conclusions

Maps of departures in the large-scale circulation have been used to elucidate the mechanisms of hydrometeorological anomalies in tropical Brazil. The drought years in the Southern Nordeste (interior Bahia) are marked by the far northerly position of the equatorial trough, a steeper pressure gradient, and strong southeasterlies to the North and strong northeasterlies to the South of the Bahia coast. These strong onshore southeasterlies resemble the mean flow patterns during the dry season (June to August) of Bahia, as apparent in

Hastenrath and Lamb (1977). The diffluent easterlies off the coast may be related to divergent flow over Bahia. The departure patterns are tested to be significant at the 20 or 5 percent level. Similar features are also found for drought years in the Northern Nordeste, except when strong southerlies cover only the coasts of Ceará and Rio Grande do Norte.

The rainfall in Ceará is concentrated in March/April and is associated with the southernmost seasonal displacement of the "ITCZ" over the equatorial western Atlantic. As the rainy season of interior Bahia precedes by about four months that of Ceará, different factors must be sought to explain the general circulation components on which Bahia's rainfall depends. Weak easterlies, a shift of meridional wind to a southerly direction, and anomalously cold water along the East Brazilian coast are noted for years with abundant rainfall in Bahia. These departure characteristics may be related to Southern frontal systems. The fronts, particularly slow-moving fronts, may bring prolonged periods of rainfall in Bahia.

Flood years in Amazonia are characterized by the deeper equatorial trough and strong North Atlantic trades. Approximately inverse departure patterns are indicated for dry years in the basin. Further analysis of the evaluation of moisture transport shall illustrate the role of these Northeast trades in terms of dry or wet conditions in Amazonia.

Thus, this mosaic of regional studies indicates that circulation mechanisms of precipitation anomalies differ distinctly between neighboring areas. The evaluation of surface circulation identifies as major factors in extreme hydrometeorological events over tropical Brazil the latitude position and intensity of the equatorial trough and frontal influences from the South Atlantic. Upper-air analysis for recent extreme years that are being initiated shall place this study of the diagnostics of climate anomalies in tropical Brazil into broader perspective.

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Part III:

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by Stefan Hastenrath

Notes:

1. Some references to areas outside the Brazil - tropical Atlantic sector have been included, because of their relevance in topic or method.

2. Asterisks indicate items listed in Conselho Nacional de Desenvolvimento Científico e Tecnológico (1980) but which could not yet be verified.

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