Frontal Influences on Northeast Brazil

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ABSTRACT

Surface observations for the 10-year period 1961–70 are analyzed for occurrences of fronts in Northeast Brazil. Cold fronts, or their remains, are found to enter the Northeast throughout the year. The southern part of the region (interior Bahia) receives much of its precipitation in the period November–February associated with frontal systems. Coastal areas, which receive maximum rainfall during the months of May–July, experience a marked increase in rainfall associated with the approach and passage of cold fronts. Even precipitation events in the extreme northern part of the region (Ceará) sometimes appear to be associated with systems which are cold-frontal in origin.

Pressure fluctuations are felt nearly simultaneously throughout the region with greatest amplitudes occurring in the south. These fluctuations are also shown to occur over a fairly broad range of longitude within tropical Brazil and may have a significant effect on the position of the equatorial trough zone over the Atlantic.

1. Introduction

The region of Northeast Brazil (see Fig. 1) is characterized by a highly variable distribution of annual rainfall. Eastern coastal areas receive up to 2000 mm or more annually, while some interior valley areas receive an annual average of less than 400 mm. Besides this areal variability there exist large year-to-year variations. A measure of these variations is the relative variability, defined as the ratio of the mean absolute deviation from the mean to the mean multiplied by 100%. The distribution of the relative variability for Northeast Brazil for the period 1931–60 is shown in Fig. 2. The areas of low relative variability (<20%) correspond to areas of large annual rainfall while the areas of high variability (>40%) correspond to arid regions (Atkinson, 1971, Chap. 6, p. 5). At times some stations within the dry interior receive annual rainfall of less than 25% of normal, while at other times the annual rainfall exceeds 200% of normal (Kousky and Chu, 1978).

The dynamical causes for such large annual variations have been investigated by Namias (1972) and Hastenrath and Heller (1977). Namias (1972) demonstrated an interconnection between the 700 mb circulation pattern over the North Atlantic and the rainfall at Quixeramobim, a station in the state of Ceará (station 22 in Fig. 1). His results showed that stronger than normal cyclonic activity near Newfoundland is associated with more than normal rainfall in Ceará. He proposed that this cyclonic activity enhances the Hadley cell circulation thereby enhancing both the northeast and

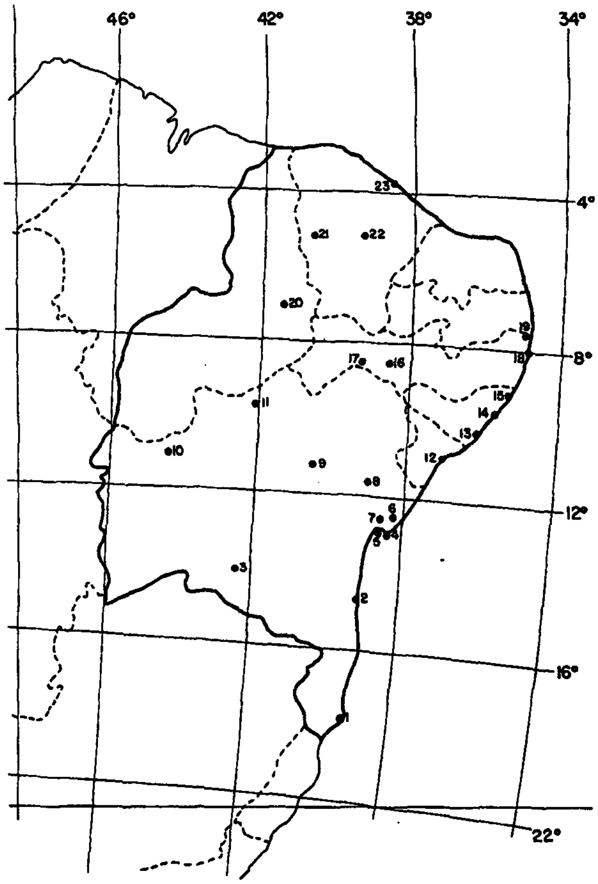

FIG. 1. Northeast Brazil and stations used in this study. Numbers correspond to those used in the text and in other diagrams adjacent to the station names.

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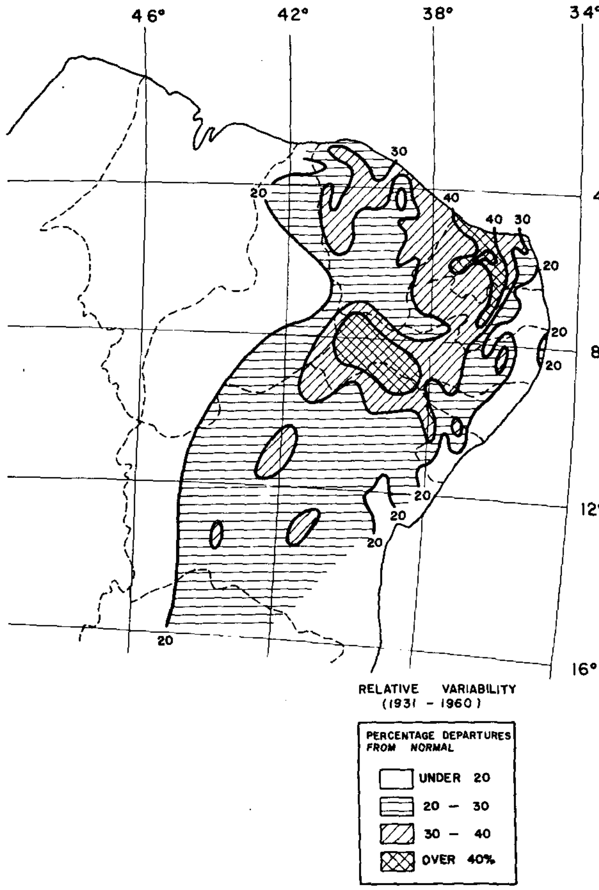

FIG. 2. Relative variability of rainfall for northeast Brazil. Analysis interval is 10%.

southeast trade winds. The enhanced southeast trades would be responsible for the higher than normal rainfall totals in the Northeast of Brazil. More recently, Hastenrath and Heller (1977) used a large number of observations to show that rainfall in the region of Ceará is closely linked to the meridional displacement and strength of the equatorial trough zone. These results are consistent with those of Namias. To support lower tropospheric cyclonic activity in the area of Newfoundland, an upper tropospheric trough would be expected just off the east coast of the United States (70°W). If one considers the upper tropospheric flow pattern to be persistent (stationary) and of wave-number 5, a fairly common pattern, then the downstream ridge position would be expected near 35°W. This ridge would support a stronger than normal subtropical high-pressure system in the central North Atlantic very close to the longitude of the eastern coast of Northeast Brazil. Such a system would strengthen and force southward the equatorial trough, thus increasing rainfall in the northern section of northeast Brazil.

The role of tropical disturbances in producing precipitation in the Northeast has also been studied. Ramos (1975) analyzed seven precipitation episodes for the period January–April 1972 and found that, on the average, rainfall systems appear to move from east to west with a speed of ~2–3° longitude day^{-1}. He noted that this is considerably slower than the typical tropical disturbance, which moves westward at ~6° longitude day^{-1}. His results also show, though this point was not explicitly stated, that the rainfall systems also move south to north with a speed approximately equal to the east to west speed. Yamazaki and Rao (1977), using a time-section of satellite pictures adapted from Wallace (1970), found the existence of westward propagating disturbances in the latitude range of 5–15°S in the Atlantic during the period June–August 1967. The speed of movement of these disturbances was found to be about 10° longitude day^{-1}, which is much greater than that found by Ramos and also much greater than the speed of movement for typical tropical disturbances. The slower speed of movement determined by Ramos may be a seasonal

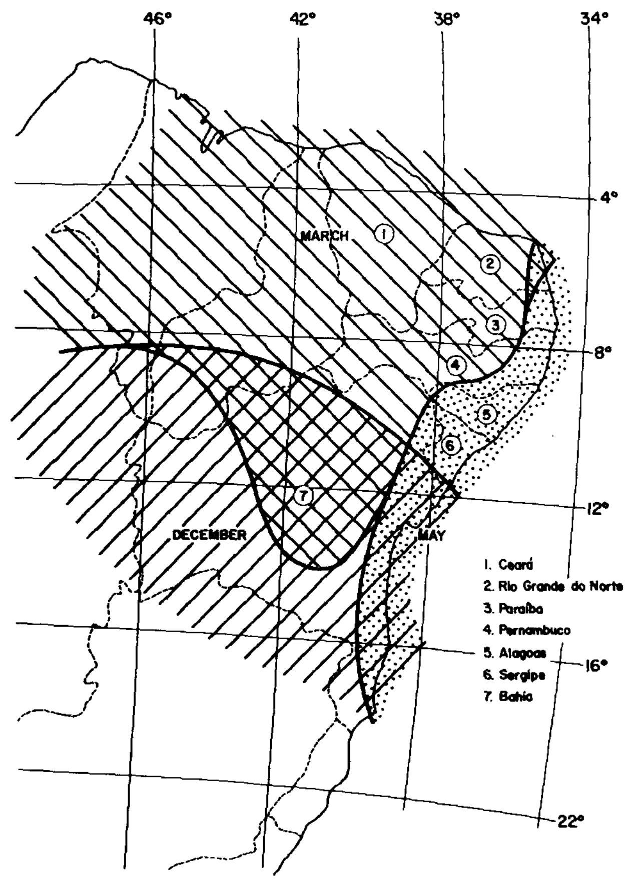

FIG. 3. Areal distribution of the month in which the mean monthly rainfall reaches a maximum. Data used are for the period 1931–1960 and were obtained from the Superintendência do Desenvolvimento do Nordeste in Recife, Pernambuco.

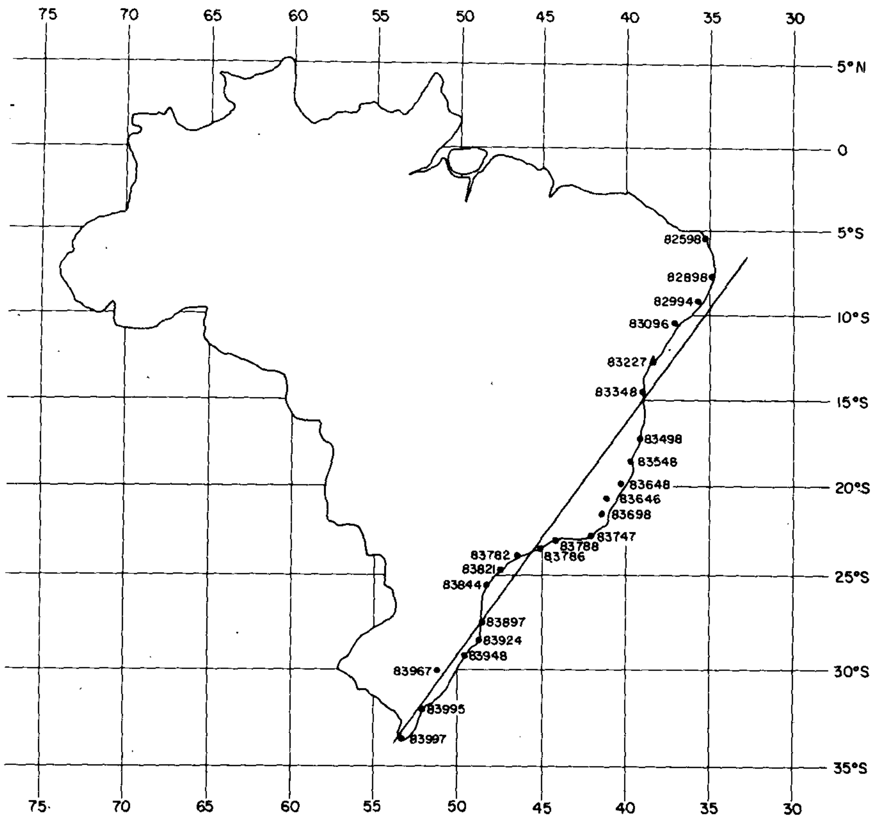

FIG. 4. Stations used in the space-time section analyses of wet-bulb temperature.

effect or may be due to the inclusion of rainfall systems which were not tropical in origin. The large amount of meridional movement of the rainfall systems, apparent in the average results presented by Ramos, tends to support the latter hypothesis.

Using areal analyses of yearly values of the percent of the 30-year annual mean rainfall, Kousky and Chu (1978) showed that the deviations in annual rainfall, in general, do not agree between the northern (Ceará) and southern (Bahia) parts of the Northeast. They suggested that Southern Hemispheric frontal activity and its variation from one year to the next might partially account for the variability in annual rainfall over the southern and coastal areas of the region.

The distribution of monthly rainfall throughout the year tends to support the idea that more than one major factor is involved in precipitation produc-

TABLE 1. Number of sustained wind shifts at Caravelas for each month during the period 1961–70. Values in parentheses indicate the number of cases which were accompanied by at least a 2°C drop in the mean wet-bulb temperature. These latter cases are referred to as cold frontal passages in the text.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Total rainfall
1961	0 (0)	0 (0)	2 (1)	3 (0)	2 (2)	2 (1)	2 (2)	1 (0)	1 (1)	2 (2)	2 (2)	2 (1)	19 (12)	921.1
1962	0 (0)	1 (1)	1 (0)	3 (2)	4 (4)	2 (2)	3 (2)	4 (2)	2 (1)	3 (2)	1 (1)	1 (1)	25 (18)	1111.0
1963	1 (0)	2 (0)	2 (0)	2 (1)	2 (2)	3 (2)	2 (2)	3 (1)	1 (1)	1 (0)	4 (0)	2 (2)	25 (11)	850.3
1964	2 (1)	2 (2)	2 (2)	2 (0)	4 (3)	3 (1)	4 (3)	2 (1)	2 (1)	1 (1)	4 (4)	3 (1)	31 (20)	1696.0
1965	0 (0)	1 (0)	3 (2)	2 (1)	2 (2)	2 (0)	3 (3)	1 (1)	4 (1)	2 (2)	2 (1)	0 (0)	22 (13)	1113.4
1966	0 (0)	0 (0)	2 (0)	2 (1)	2 (2)	2 (1)	2 (0)	3 (3)	3 (2)	2 (1)	2 (1)	1 (0)	21 (11)	1013.6
1967	0 (0)	0 (0)	2 (0)	3 (2)	2 (2)	2 (2)	2 (1)	1 (0)	3 (3)	1 (0)	3 (2)	3 (2)	22 (14)	1153.1
1968	1 (0)	2 (1)	2 (2)	3 (3)	5 (5)	2 (2)	3 (1)	1 (1)	2 (2)	3 (3)	3 (2)	1 (1)	28 (23)	1208.1
1969	1 (0)	1 (0)	1 (1)	2 (1)	3 (1)	3 (3)	3 (3)	3 (1)	1 (1)	2 (1)	1 (0)	4 (3)	25 (15)	1075.5
1970	1 (1)	2 (0)	2 (0)	2 (1)	1 (1)	2 (1)	3 (2)	2 (1)	3 (2)	5 (4)	3 (1)	1 (1)	27 (15)	1247.8
	6 (2)	11 (4)	19 (8)	24 (12)	27 (24)	23 (15)	27 (19)	21 (11)	22 (15)	22 (16)	25 (14)	18 (12)	245 (152)	

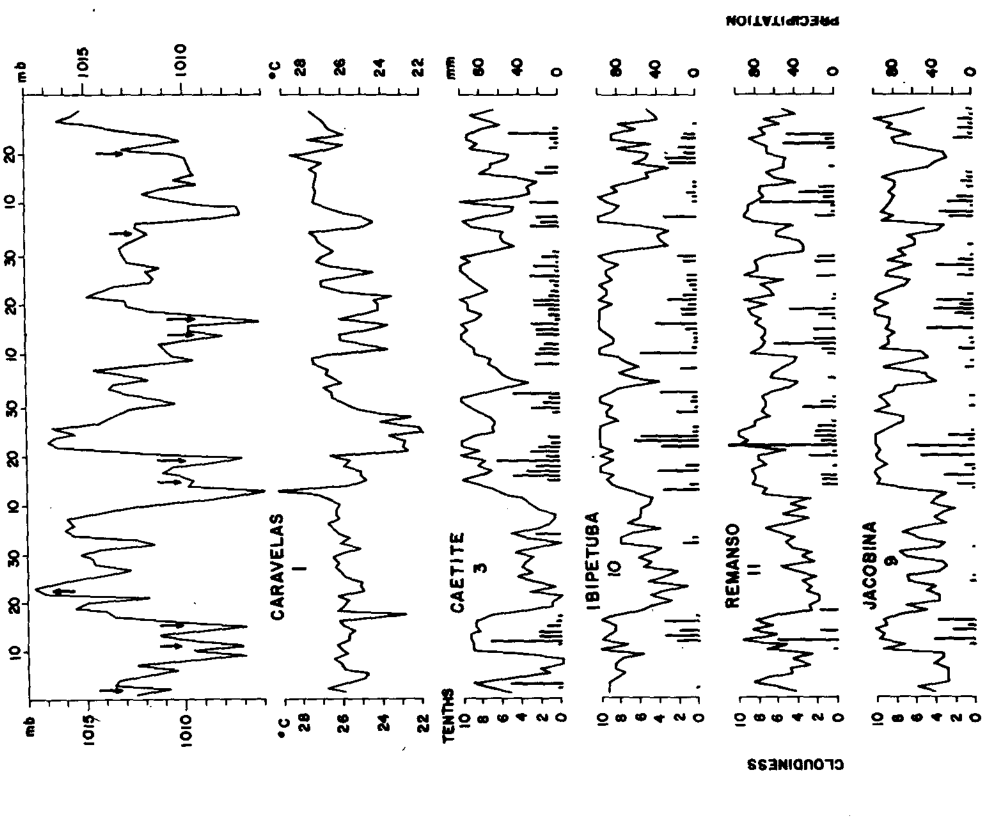

FIG. 5. A comparison of the time series of pressure and temperature for Caravelas with cloudiness and rainfall at selected stations in Bahia for the period November 1963–February 1964. Wind shifts at Caravelas are indicated by arrows.

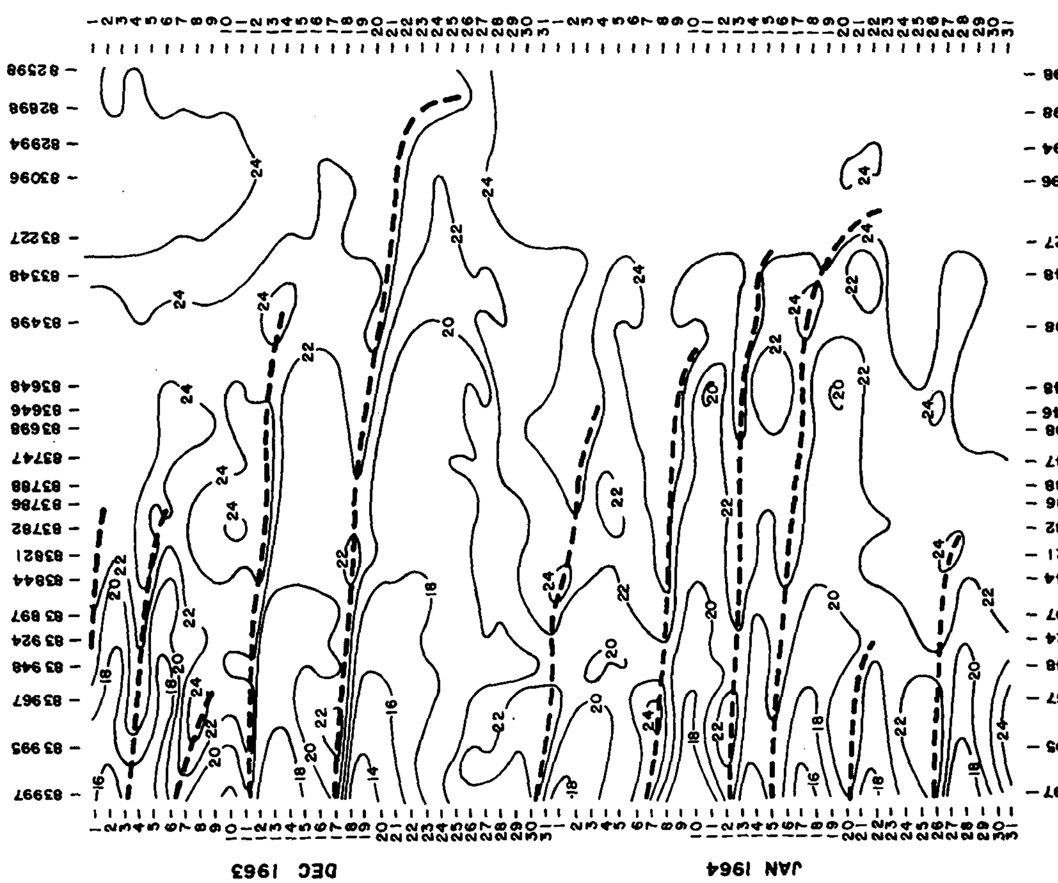

FIG. 6. Space-time section of wet-bulb temperature for December 1963–January 1964. Analysis interval is 2°C. Cold fronts are indicated by dashed lines.

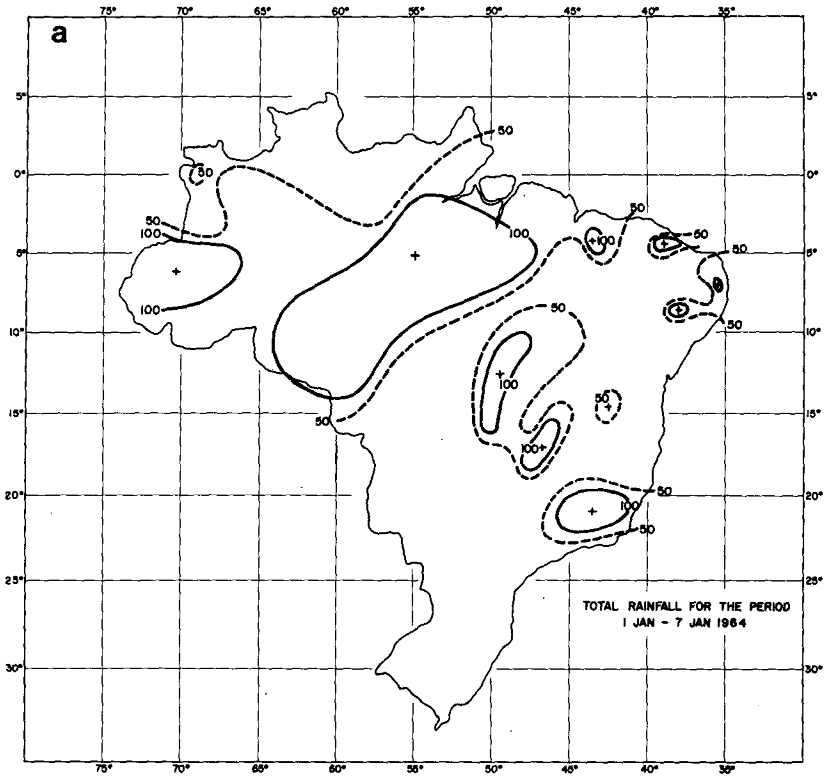

FIG. 7a. Distribution of total rainfall (mm) for the period 1–7 January 1964.

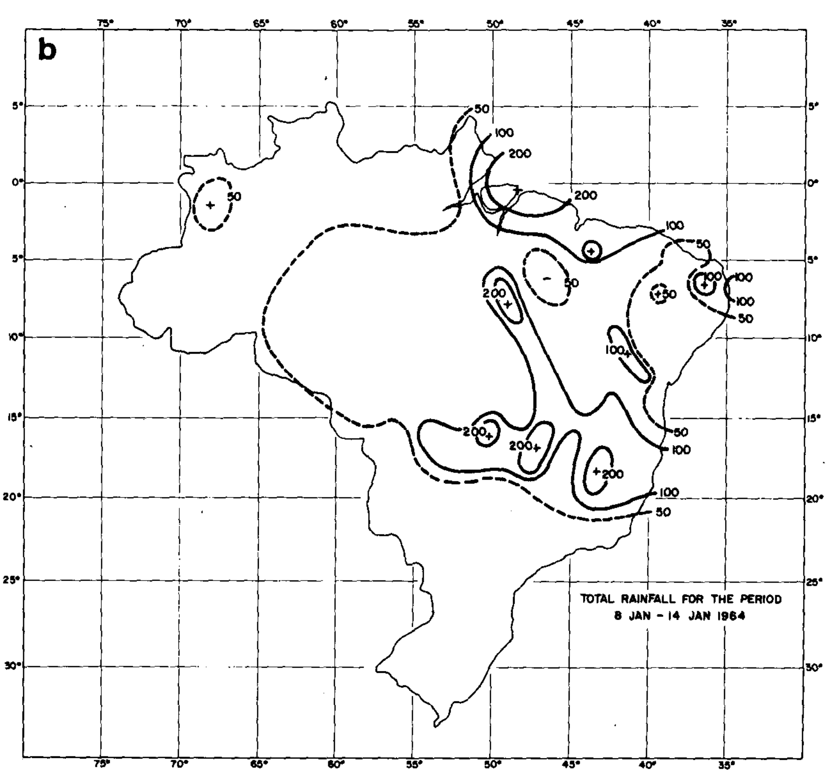

FIG. 7b. As in Fig. 7a except for 8–14 January 1964.

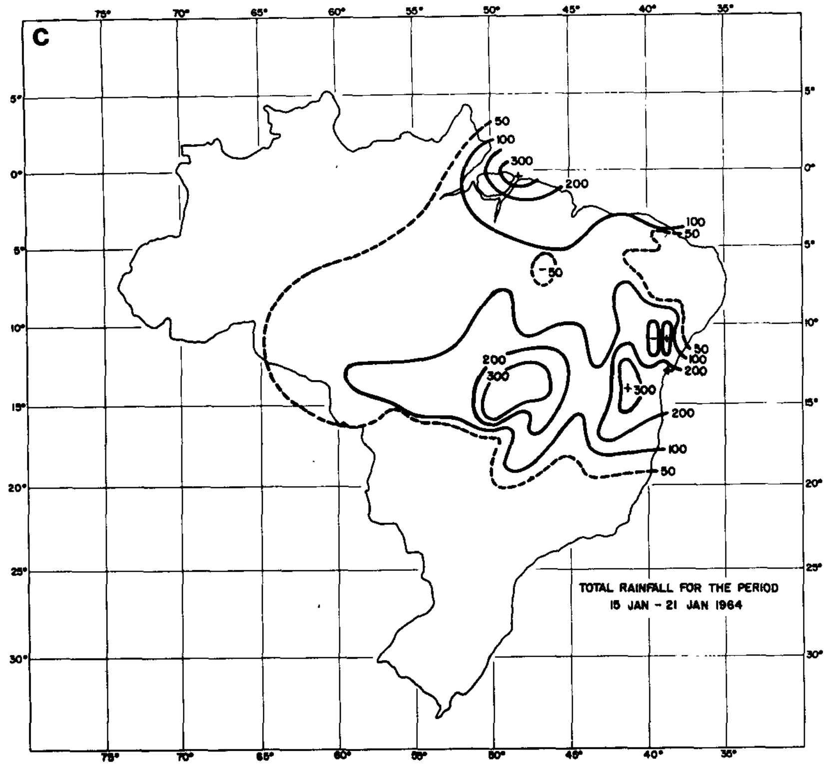

FIG. 7c. As in Fig. 7a except for 15–21 January 1964.

tion in the Northeast. Rainfall reaches a monthly maximum in the area of Ceará, western Rio Grande do Norte and interior sections of Paraíba and Pernambuco during March and April (Fig. 3). This agrees well with the time of the southernmost position of the equatorial trough zone. Interior southern Bahia receives its maximum rainfall in December, while coastal sections from eastern Rio Grande do Norte to southern Bahia receive their maximum rainfall during the Southern Hemisphere fall and winter (May–July). There are certain overlap regions which tend to get double maxima, such as central and northern Bahia (December and March) and coastal Bahia (December and May). These features closely resemble results obtained by Strang (1972).

This paper explores the possibility that frontal systems have an important influence on the region of Northeast Brazil both in shaping the distribution of precipitation throughout the year and in producing extreme events.

2. Data analysis

The primary data source for this study was a collection of surface observations made by the Instituto Nacional de Meteorologia do Brasil. These data, for the period 1961–70, have been processed and placed on magnetic tape by the personnel at the Instituto de Pesquisas Espaciais. Available are station pressure, temperature, wet-bulb temperature, relative humidity, wind direction (to eight points of the compass), wind speed, cloudiness (in tenths) and precipitation totals for three daily observation times (1200, 1800 and 0000 GMT).

To investigate the effects of fronts on the region of the Northeast, time series of station pressure, cloudiness and 24 h precipitation totals were constructed. To remove the effect of the diurnal pressure oscillation the three daily observations were averaged and the resultant values used in constructing the time series. The time series of cloudiness were constructed in the same manner. These time series were then compared to the occurrences of fronts at a station in the extreme southern part of the region. Caravelas (station 1, Fig. 1) was chosen as the basis for comparison because of its location and completeness of record. Frontal passages at Caravelas were based on 1) a significant and sustained wind shift to a southerly direction, 2) a drop in the mean daily wet-bulb temperature of 2°C, and 3) continuity with stations further South.

In this paper the term "cold front" will be applied to those synoptic systems which satisfy each of the above criteria, i.e., originated at higher latitudes as distinct cold fronts and, at the latitude of Caravelas, still have identifiable wind and thermal support. Also considered in this paper are those systems

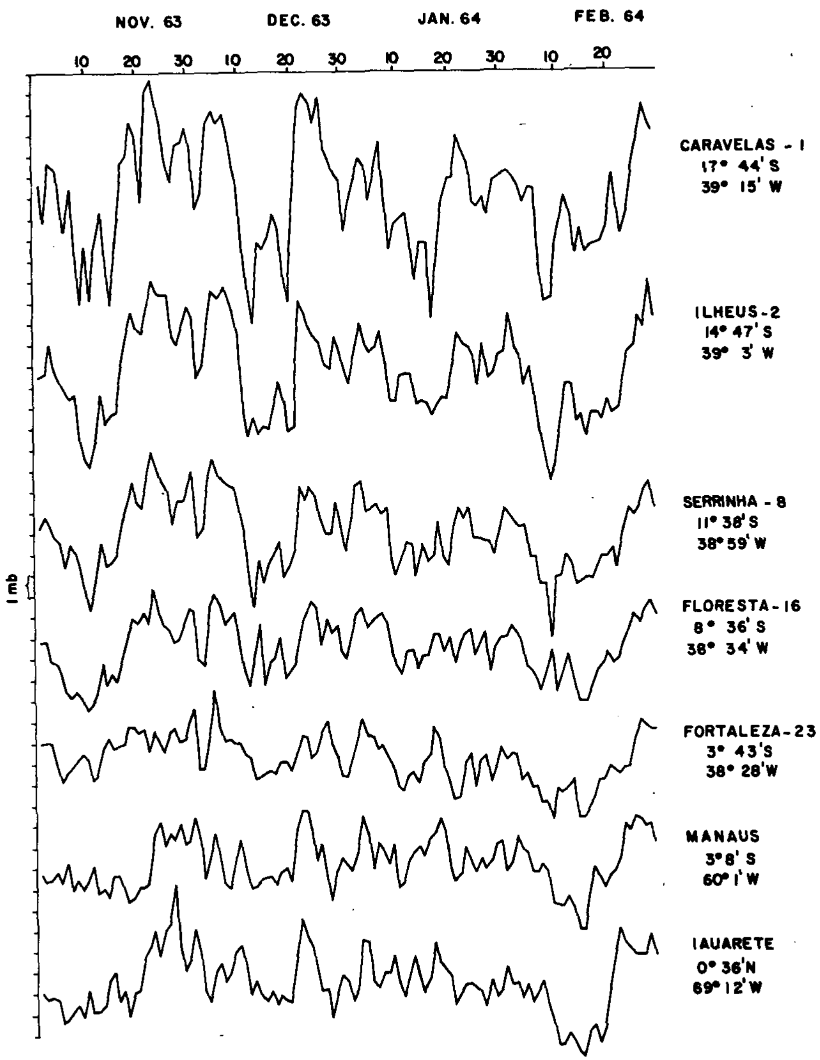

FIG. 8. Time series of pressure for selected stations in Northeast and northern Brazil for the period November 1963–February 1964.

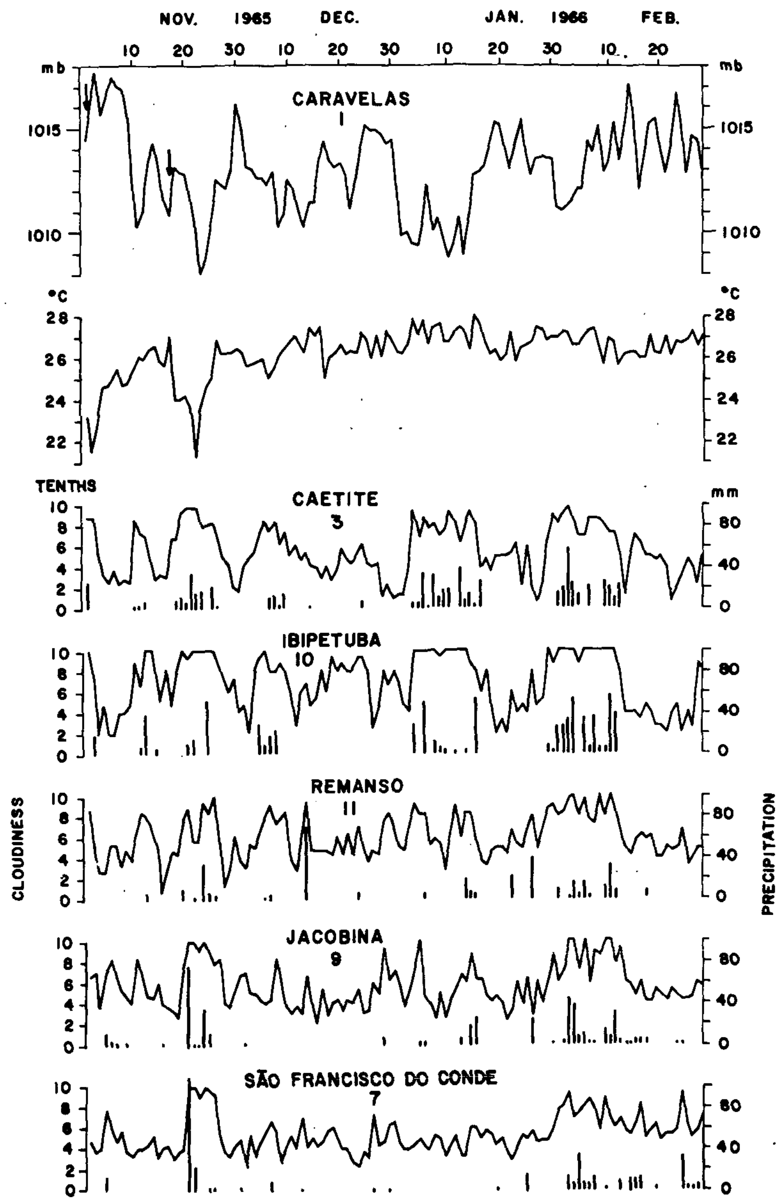

FIG. 9. As in Fig. 5 except for the period November 1965–February 1966.

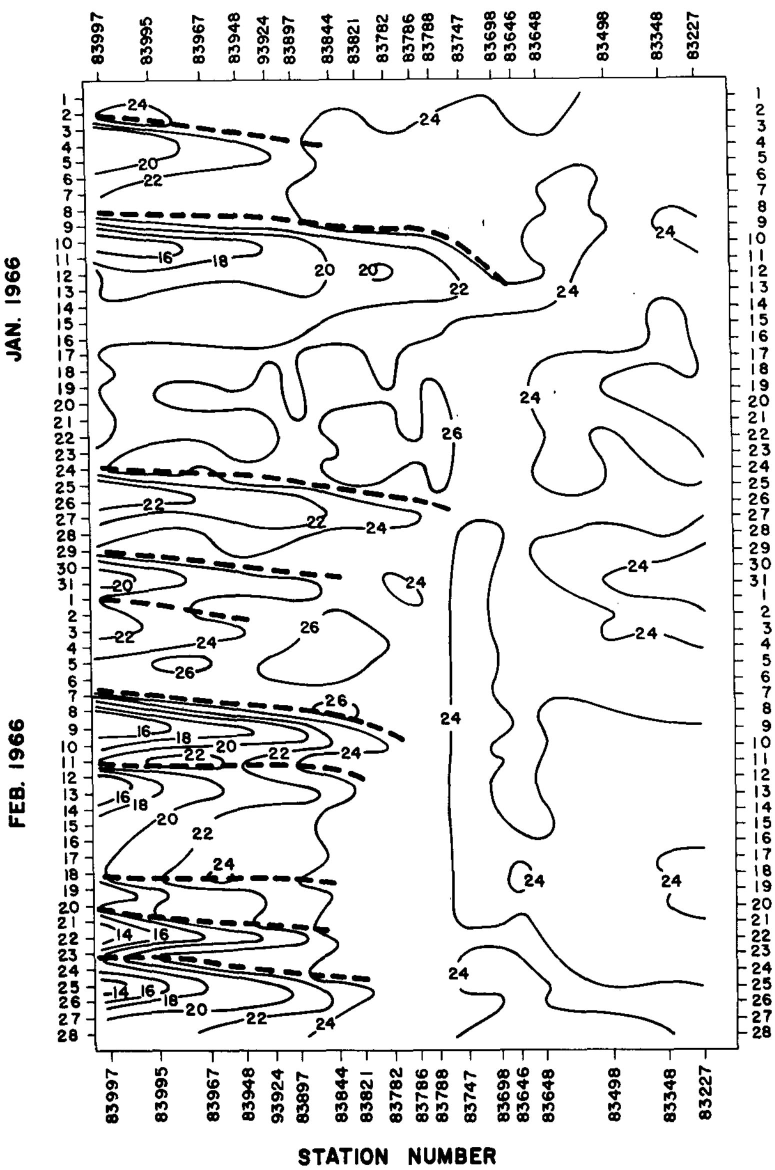

FIG. 10. As in Fig. 6 except for January–February 1966.

for which only the first and third criteria are met. These systems, referred to hereafter as "wind shifts," include cold fronts in various stages of dissipation which may still be active weather producers.

To demonstrate continuity with stations further south, space-time sections of mean daily wet-bulb temperature (T_w) were constructed. The stations used in these sections are shown in Fig. 4. The wet-bulb temperature is nearly conservative with respect to evaporation of falling rain. However, it is not conservative when condensation (dew formation) and surface evaporation take place. By taking the daily arithmetic mean of T_w at the three observation times these effects are greatly reduced.

3. Results

For the 10-year period available, 245 cases were found which have a significant wind shift at Caravelas and continuity with stations further south in Brazil. Of these cases 152 also have a drop of 2° in T_w and will be hereafter referred to as cold-frontal passages. The number of wind shifts are presented month by month in Table 1. The cold frontal passages are given in parentheses. It is evident that cold fronts or their remains may be expected in the region of southern Bahia throughout the entire year, with the greatest frequencies occurring during the months of March to December,

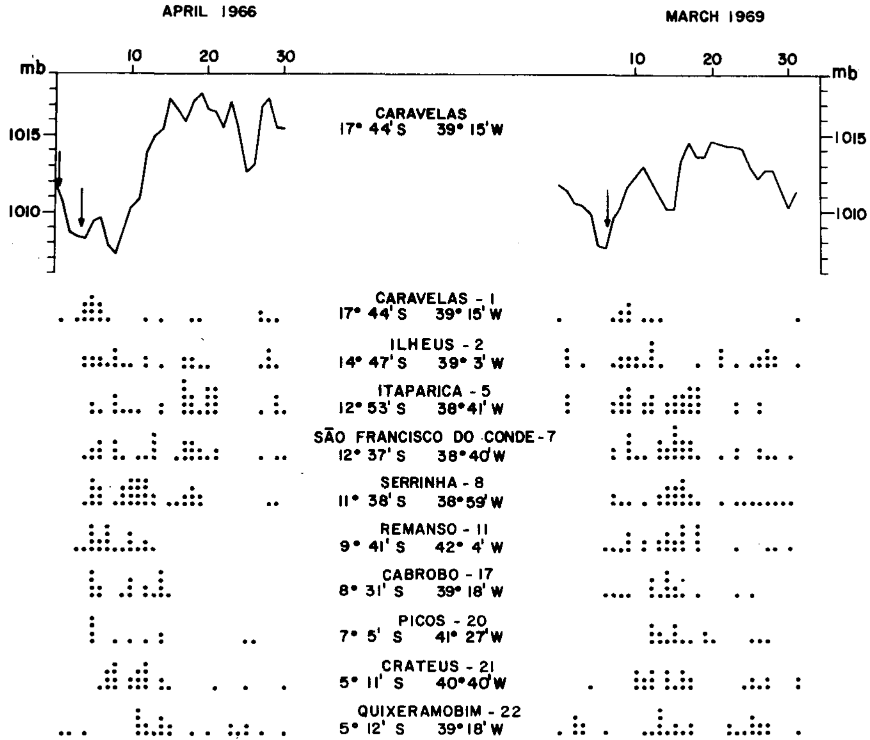

FIG. 11. A comparison of the time series of pressure and temperature at Caravelas with daily rainfall totals for selected stations throughout the Northeast for April 1966 and March 1969. The number of dots in the vertical correspond to different rainfall categories as: 1 dot (1–10 mm), 2 dots (10.1–25 mm), 3 dots (25.1–50 mm), 4 dots (50.1–100 mm), 5 dots (100.1–200 mm) and 6 dots (>200 mm).

corresponding to the Southern Hemisphere fall, winter and spring seasons. Only during the summer season (January–February) are there fewer frontal passages. Also evident from Table 1 is a variability in the annual number of frontal passages. Comparing the total number of cold frontal passages in each year with the total rainfall for that year, one notes a tendency for the years of greatest rainfall totals to correspond with the years of greatest number of frontal passages.

To explore the relationship between the presence of frontal systems and precipitation over the entire Northeast, several periods were selected and analyzed by comparing the time series of rainfall totals and cloudiness with the presence of frontal systems. The stations used in these comparisons are indicated in Fig. 1. Such a comparison for the period November 1963–February 1964 is shown in Fig. 5. Evidently, frontal systems or their remains, which enter southern Bahia, have a significant effect on both cloudiness and rainfall for the entire state. This is particularly true for the periods 15–30 December and 10–30 January. The space-time section of T_w (Fig. 6), which corresponds to the period December 1963–January 1964, shows the northeastward advance of a fairly strong cold front during 17–21 December which reached coastal areas near 10°S. Also evident is a series of three cold fronts, each successive front penetrating further north than the preceding one, which affected the region during 7–20 January. Note the pressure minima at Caravelas (Fig. 5) corresponding to each of these fronts.

A closer look at the period 1–21 January 1964 (Figs. 7a–7c) illustrates the effects some fronts have on the rainfall distribution in Brazil. A fairly weak cold front entered southern Brazil on 31 December and moved slowly northeastward reaching southeastern Brazil on 3 January where it dissipated on the 4th (Fig. 6). The maximum in precipitation over southeast Brazil (Fig. 7a) is probably due to the influence of this front. On 8 January a stronger cold front entered Brazil and moved rapidly northeastward reaching southeast Brazil on the 9th. This front became quasi-stationary just south of Caravelas and continued in the area until the 12th. On the 13th another cold front entered southern Brazil and progressed northeastward passing Caravelas on the 14th. Fig. 7b shows how the rainfall was greatly enhanced over southeastern and central Brazil during the seven day period 8–14 January probably due to the action of these cold fronts. Still another cold front entered Brazil on the 16th, passed Caravelas on the 17th and became quasi-stationary near 12°S until the 22nd. This frontal system was associated with very heavy rains in many sections of central and eastern Brazil (Fig. 7c).

During this three-week period a marked increase is noted in rainfall over eastern and northern Brazil, as well as a general eastward shift in the rainfall activity from western Brazil to eastern Brazil. During the final seven-day period the presence of the cold front along the coast of central Bahia provoked locally very heavy rains. The cold front passed Salvador (station 4, Fig. 1) on the 19th. Between 1800 GMT on the 19th and 1200 GMT on the 20th 82.4 mm of rain fell. At a nearby station, Itaperica (station 5, Fig. 1), 399.8 mm fell during the same period, bringing the seven-day total to 782.4 mm, which is nearly one third of the mean annual rainfall for the station.

The increase in rainfall along the coast of northern Brazil (see Figs. 7a–7c) may also be related, in an indirect manner, to the frontal activity over central and eastern Brazil. The pressure variations at Caravelas (Fig. 5) are also present, though in diminished amplitude, at low latitude stations even though most of these stations do not experience frontal passages (see Fig. 8). It seems plausible, therefore, to suggest that the surface pressure variations are associated with changes in the tropospheric

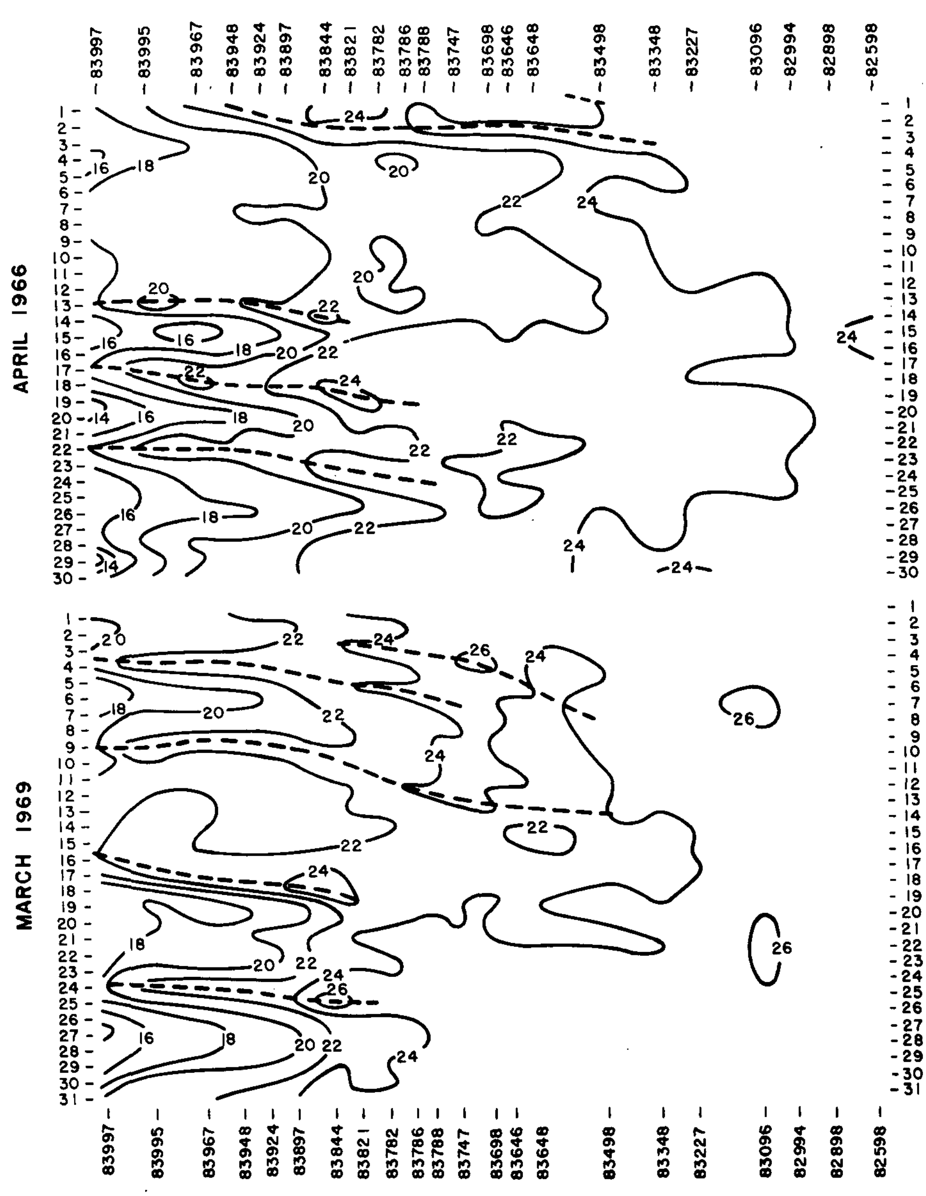

FIG. 12. As in Fig. 6 except for April 1966 and March 1969.

FIG. 13. Visible ESSA-8 images for 7 March 1969.

circulation pattern over Brazil. For example, the relatively low pressure observed between 8–13 November would correspond to a mid-tropospheric trough over Brazil, while the relatively high pressure between 15 November and 9 December would correspond to the absence of the trough or the presence of a ridge. Frontal systems and their attendant mid-tropospheric troughs, which extend equatorward, would lower surface pressure at low latitudes thus favoring the southward movement of the equatorial trough zone. This would increase rainfall along the coast of northern Brazil, as well as eventually supply additional moisture to the frontal systems. In this respect, it is interesting to note that the period November 1963–February 1964, with its large number of active fronts at low latitudes, coincided with a more southward than normal displacement of the intertropical trough zone (see Hastenrath and Heller, 1977).

During the period of November 1963–February 1964 a total of ten cases of sustained wind shift occurred at Caravelas. Five of these cases had characteristics of cold frontal passages. In contrast, during the period of November 1965–February 1966 only two cases of sustained wind shift occurred with only one of these having cold frontal characteristics. Rainfall during this latter period was generally below normal in northeastern Bahia and near or above normal in western and southern sections of the state. The time series of pressure and temperature for Caravelas, along with the time series of cloudiness and rainfall at selected stations in Bahia for this period, are shown in Fig. 9. Although no cold frontal passages were observed at Caravelas during January and February a large amount of rain fell over interior and southern Bahia, mainly confined to the periods of 3–16 January and 31 January–12 February. During both of these periods pressure minima were experienced at Caravelas.

The space-time section of T_w for the period January–February 1966 (Fig. 10) reveals that the first half of January was influenced by two cold frontal systems. The first of these entered southern Brazil on the 3rd and dissipated by the 5th. The second and stronger front entered Brazil on the 9th and progressed rapidly northeastward reaching southeast Brazil on the 10th. This frontal system then slowed down as it dissipated by the 13th. Rainfall activity continued in southern and western Bahia until the 16th. Although the field of T_w no longer indicated the existence of a frontal zone in southeastern Brazil, it is probable that a zone of convergence and a residual surface pressure trough still existed. It wasn't until the 15th that the pressure at Caravelas (see Fig. 9) began to rise rapidly, indicating dissipation of the surface pressure trough.

The period 16–24 January was free of frontal activity in southern and southeastern Brazil and corresponds to a period of relatively high pressure at Caravelas (Fig. 9). Another series of cold fronts began to enter Brazil on 24 January. The cold fronts which entered southern Brazil on 29 January and 1 February were quite weak and made very little progress northeastward. On 7 February a stronger cold front entered Brazil and subsequently moved to southeast Brazil by the 9th. During the first ten days of February surface pressure remained relatively low and rainfall was quite heavy over western and southern parts of Bahia.

During the period November 1965–February 1966 the equatorward penetration of frontal systems was much less than in the November 1963–February 1964 case. However, the reduced surface pressure over central Brazil associated with each period of frontal activity would still favor the influx of moisture into this region from the Amazon basin and the Atlantic off the coast of northern Brazil. This moisture would in turn be supplied to the frontal systems over southeastern Brazil. Even though frontal systems did not actually enter the Northeast they were close enough so that Bahia felt the effects of increased convective activity associated with them.

It is evident that frontal systems have a pronounced effect on weather over the southern part of northeast Brazil during the summer months.

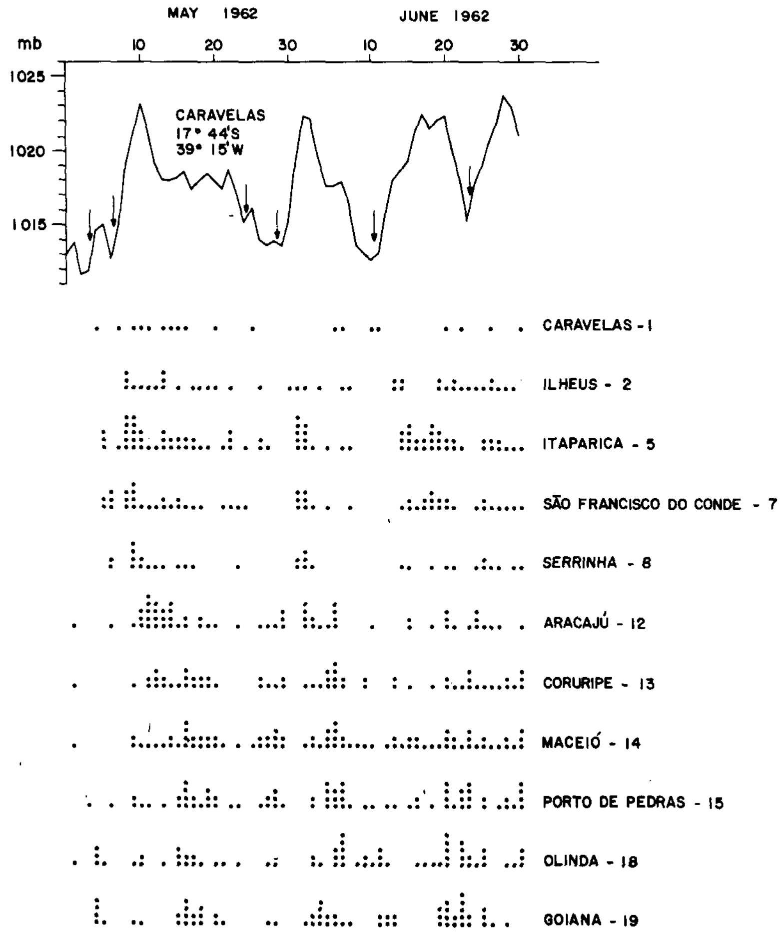

FIG. 14. As in Fig. 11 except for coastal stations during the period May–June 1962.

To investigate the effects of frontal systems on the Northeast during the fall and winter months several periods were chosen for analysis. As an example, consider the case of April 1966 (Fig. 11). The remains of a cold front passed Caravelas on the 1st. This was followed on the 4th by a cold front which had entered southern Brazil on the 1st (Fig. 12). This frontal system remained quasi-stationary along the coast of central Bahia, as evident by the south–north gradient in T_w shown in Fig. 12, until after the 14th. The pressure minimum on the 8th at Caravelas (Fig. 11) probably corresponds to the formation of a wave along this front. This is supported by an undulation in the T_w analysis shown in Fig. 12. Most stations in Fig. 11 show a maximum in rainfall within a week to ten days after the cold front passed Caravelas. Stations in the southern part of the region, in addition to the rainfall activity associated with the first frontal system (4–13 April), show increased rainfall activity during the period 17–21 April. This latter activity may have been associated with a cold front that entered southern Brazil on the 17th (Fig. 12).

During March 1969, also shown in Fig. 11, a wind shift occurred at Caravelas on the 7th. It is evident that the heaviest precipitation at each station occurred after the 7th and that this activity progressed from south to north (top to bottom in the diagram). Fig. 12 shows a somewhat complicated situation for this period. Apparently a weak cold front was present in southeast Brazil during 1–3 March. On the 4th a second cold front entered southern Brazil and moved northeastward possibly merging with the first front. On the 9th a third cold front entered Brazil and moved northeastward. This frontal system may also have merged with the previous frontal systems serving to reinforce the frontal zone near Caravelas.

An inspection of ESSA-8 visible satellite images for this period revealed that on 4 March a cold front, with a weak frontal band, was situated in Southeast Brazil. By 6 March the frontal band had intensified considerably, possibly due to the merging of the first two frontal zones. The ESSA-8 images for the two daytime passes on 7 March are shown in Fig. 13. The frontal band, extending from Bahia

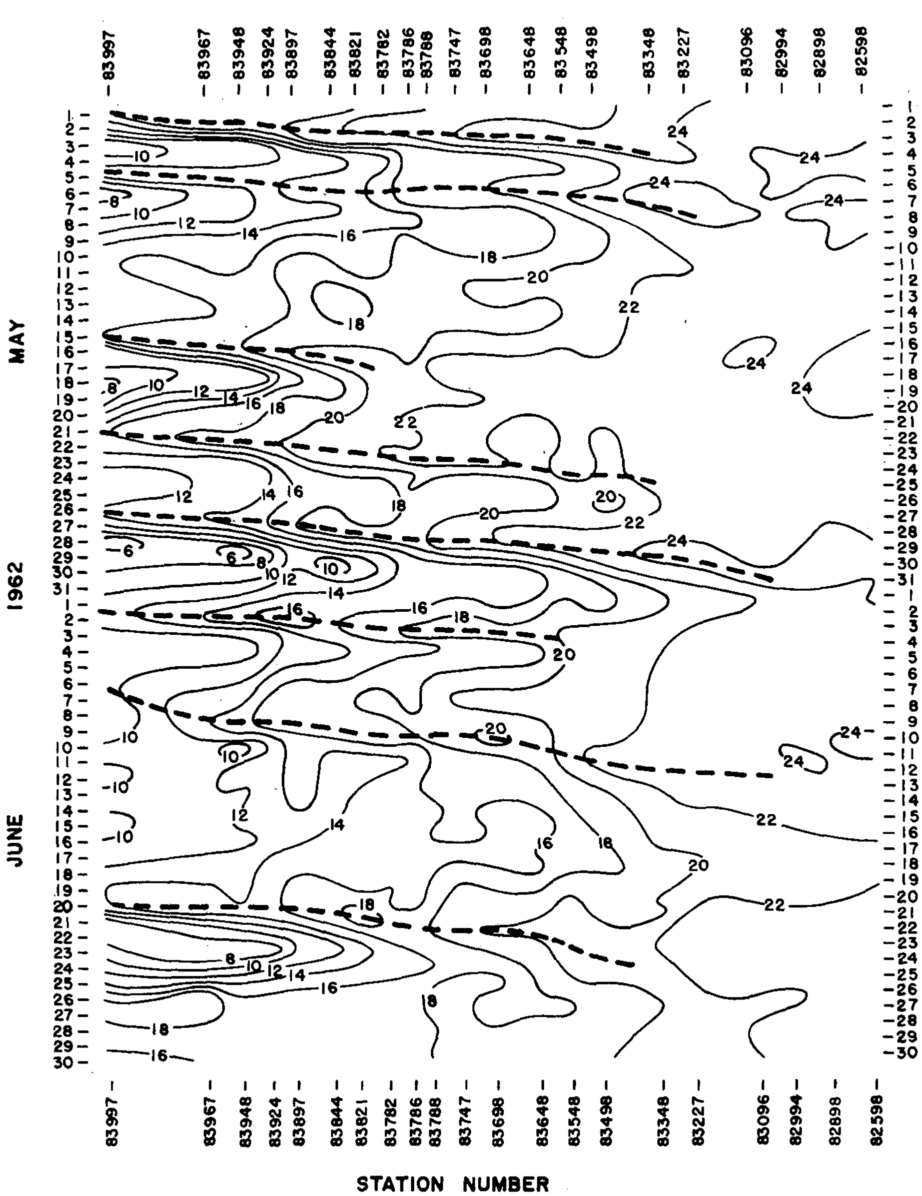

FIG. 15. As in Fig. 6 except for May–June 1962.

southeastward over the Atlantic is readily noted. Also evident is the cloudiness associated with the equatorial trough zone located over the Atlantic at the latitude of extreme northern Brazil. By the 10th this band of cloudiness had shifted south to a position very close to the coast of Ceará. This southward shift may be in response to the low surface pressure which existed in the Northeast between the 1st and the 10th. Note that Quixeramobim (station 22, Fig. 1) received a maximum in rainfall between the 10th and the 15th. The satellite images show that between the 15th and 19th the frontal band, and presumably the front, gradually dissipated.

As previously noted, the eastern coastal areas of northeast Brazil receive their maximum monthly rainfall in the period May–July. Normally the equatorial trough zone has already retreated to the north, while cold frontal frequency in the Northeast is at a maximum (Table 1). The comparison between stations for the period May–June 1962 is shown in Fig. 14. Again it is evident that the heaviest precipitation episodes occur after cold fronts have passed Caravelas and that these events move from south to north (top to bottom in the diagram). It is also evident from Fig. 14 that there is a general background of rainfall occurring throughout the period, which may be due to convergence between the land-sea breeze circulation and the mean southeasterly flow.

The space-time section of T_w for this period (Fig. 15) shows that a strong cold front entered Brazil on 1 May and moved rapidly northeastward passing

Caravelas on the 3rd. This frontal zone, apparently reinforced by a cold front which entered Brazil on the 5th, remained quite strong through the 10th. Between the 10th and the 15th it gradually dissipated. Another major frontal zone entered Brazil on the 27th, passed Caravelas on the 29th and continued northward to about 11°S on the 31st. Throughout most of June frontal zones of variable intensity existed along the coast of Bahia, as evident by the continued presence of a south–north gradient of T_w in this region.

In all the cases discussed previously the time-series of pressure for individual stations were compared to those for Caravelas. As Fig. 8 illustrates, most pressure minima and maxima occur nearly simultaneously at all stations and the amplitudes of the pressure fluctuations decrease equatorward. Also included in Fig. 8 are the time series of pressure for two stations in Amazonas. These series are quite similar to those for the Northeast, thus demonstrating that the synoptic systems involved affect a fairly large longitudinal as well as latitudinal range.

4. Summary and conclusions

The examples discussed here, which are representative of the 10-year data sample, show that frontal systems or their remains 1) penetrate the southern part of the Northeast throughout the year; 2) play an important role in the December–January maximum in monthly rainfall experienced in the southern part of the Northeast (Bahia); 3) are associated with increased rainfall along the coast from Bahia to Rio Grande do Norte during the fall and winter months; 4) at times affect rainfall as far north as Ceará; and 5) lower surface pressure at low latitudes, thus favoring the southward movement of the equatorial trough zone.

Although there seems to be some agreement between annual rainfall and frontal frequency in the southern part of the Northeast, it is apparent that it is not as much the quantity of fronts as their character which produces significant effects on the region. Slow moving fronts, possibly associated with wave formation, may be associated with prolonged periods of rainfall, which at times produce excessive amounts.

The nearly simultaneous nature of the pressure fluctuations, which occur over a fairly broad longitudinal range within tropical Brazil, may be the same type of feature noted within tropical latitudes by other researchers (e.g., Brier and Simpson, 1969). These fluctuations may result from variations in the midlatitude and subtropical latitude circulation patterns. This type of latitudinal coupling has been discussed by Riehl (1977) in a paper dealing with deep intrusions of midlatitude troughs into the tropics. Such coupling would cause the surface pressure to decrease and rainfall to increase within the tropics when a trough is extending equatorward.

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REFERENCES

Atkinson, G. D., 1971: Forecasters guide to tropical meteorology. Air Weather Service, Tech. Rep. No. 240, Scott Air Force Base, IL.

Brier, G. W., and J. Simpson, 1969: Tropical cloudiness and rainfall related to pressure and tidal variations. *Quart. J. Roy. Meteor. Soc.*, **95**, 120–147.

Hastenrath, S., and L. Heller, 1977: Dynamics of climate hazards in Northeast Brazil. *Quart. J. Roy. Meteor. Soc.*, **103**, 77–92.

Kousky, V. E., and P. S. Chu, 1978: Fluctuations in annual rainfall for Northeast Brazil. *J. Meteor. Soc. Japan*, **56**, 457–465.

Namias, J., 1972: Influence of northern hemisphere general circulation on drought in northeast Brazil. *Tellus*, **24**, 336–342.

Ramos, R. P. L., 1975: Precipitation characteristics in the Northeast Brazil dry region. *J. Geophys. Res.*, **80**, 1665–1678.

Riehl, H., 1977: Venezuelan rain systems and the general circulation of the summer tropics II: Relations between low and high latitudes. *Mon. Wea. Rev.*, **105**, 1421–1433.

Strang, D. M. G., 1972: Climatological analysis of rainfall normals in Northeastern Brazil. Pap. No. EAE-M-02/72, 70 pp. [Available from Centro Técnico Aeroespacial, 12.200—São José dos Campos, São Paulo].

Wallace, J. M., 1970: Time-longitude sections of tropical cloudiness December 1966–November 1967. ESSA Tech Rep. NESC.56, National Environmental Satellite Center, Washington, DC, 37 pp.

Yamazaki, Y., and V. B. Rao, 1977: Tropical cloudiness over the South Atlantic Ocean. *J. Meteor. Soc. Japan*, **55**, 205–207.