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Inter-annual and seasonal variations in the structure and energetics of the atmosphere over northeast Brazil

By VALDO SILVA MARQUES[1], V. BRAHMANANDA RAO and LUIZ CARLOS B. MOLION,
Instituto de Pesquisas Espaciais—INPE, Conselho Nacional de Desenvolvimento Científico e Technológico—CNPq, São José dos Campos, S.P., Brazil

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ABSTRACT

Inter-annual and seasonal variations of energetics over northeast Brazil are discussed. A cylindrical boundary having 11 aerological stations has been chosen for the study. Mass and energy fluxes are evaluated for the dry and wet seasons and also for the dry and wet years. During the wet period, there is inward mass flux in the lower levels and outward mass flux in the upper levels. During the dry period there is inward mass flux in the middle levels with outward mass flux above and below.

Variations in the vertical profiles of the energy parameters suggest that the rainfall variations in the NE Brazil are not of local origin but are connected to the variations of the general circulation in the tropics.

Water vapor flux calculations showed that during the wet period there is a net import of water vapor and during the dry period a net export.

1. Introduction

Northeast (NE) Brazil experiences highly variable rainfall both in space and time. Although the coastal region receives a rainfall of 2000 mm annually, portions of the semi-arid interior receive less than 400 mm (Strang, 1972; Kousky and Chu, 1978). The principal rainy season is rather short and occurs in the months of March, April and May. The study of the nature and variability of climate of this region is particularly important because of its high population, whose survival depends critically on rainfall. There have been some studies which attempt to understand the nature of the rainfall variability in this region (Moura and Shukla, 1981 and references cited therein).

Most of the observational studies regarding the climate of NE Brazil utilized only surface data, and those which did use upper air data used only a short series of data over very few stations. This is due to lack of well-distributed upper air stations in this region. Fortunately, since the beginning of the 70s a reasonably well distributed network of upper air stations started operating regularly in NE Brazil. This allows us to study the upper air characteristics of this region.

The purpose of the present paper is to investigate the upper air conditions of NE Brazil with the aim of recognizing the differences between the dry and wet epochs. Specifically, we define a cylinder whose base covers most of the NE Brazil area. Defining a cylinder facilitates the calculation of energy integrals as can be seen in Section 5. The energy and water vapor contents as well as their fluxes are calculated for dry and wet periods. The results show some interesting differences between the dry and wet periods.

2. Area of the study and data source

We define a cylinder as shown in Fig. 1, containing 9 Rs/Rawin and 2 pilot baloon stations.

[1] Permanent address: Departamento de Meteorologia, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil.

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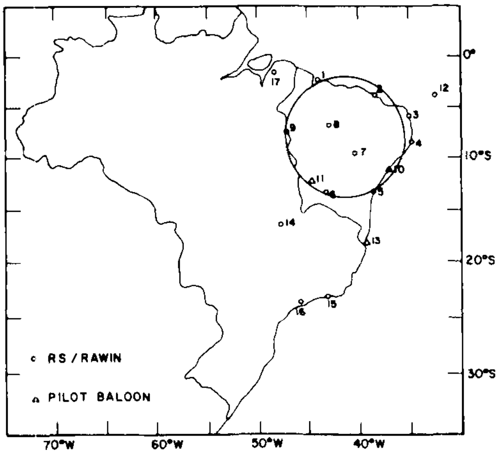

Fig. 1. Station location and the definition of cylinder over northeast Brazil.

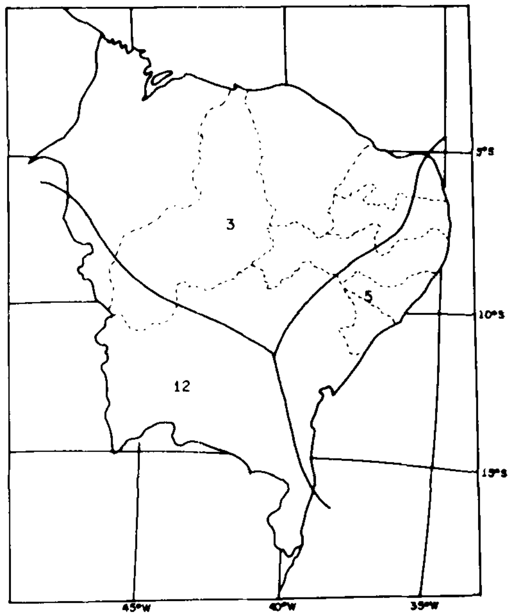

Fig. 2. Precipitation regimes over northeast Brazil with their principal months of rainfall, December (12), March (3) and May (5).

This cylinder, apart from covering most of NE Brazil, facilitates the integration of the equations for the estimates of energy fluxes. The area enclosed by the cylinder is about 10^6 km^2 and extends in the vertical up to 100 mb.

Most of the data for the present study are obtained from the Monthly climatic data for the world (U.S. Department of Commerce) 1971–78. These contain monthly means of temperature, dew point temperature, geopotential height and direction and speed of the wind at levels 850, 700, 500, 300, 200, 150 and 100 mb for the 8-year period. All the data are checked for consistency. For example, the vertical temperature distribution is adjusted such that the lapse rate does not exceed the dry adiabatic lapse rate, and the geopotential height is adjusted to be consistent with the hydrostatic approximation. Further, the missing data are inserted wherever it is possible, with the original data sources at the Instituto Nacional de Meteorologia and the Instituto de Pesquisas Espaciais, both in Brazil.

3. Analysis of precipitation

Precipitation is perhaps the principal meteorological variable which characterizes the climate in the tropics (Hantell and Peyinghaus, 1976). Thus in NE Brazil, precipitation anomalies determine climatic variations. The purpose of this section is to determine the periods which are later used for the study of seasonal and inter-annual variations. Strang (1972), using the rainfall data of NE Brazil for the period 1931–60, noted 3 seasons of rainfall. The principal months of each of these seasons are December (12), March (3) and May (5); the areas which are characterized by these seasons are shown in Fig. 2. Thus it is reasonable to take March–April–May as the principal rainy

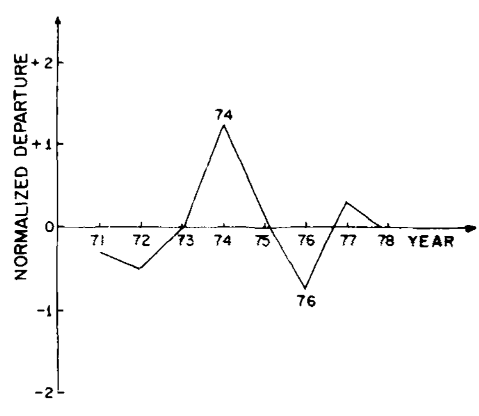

Fig. 3. Normalized departure of annual precipitation based on 58 stations in north east Brazil.

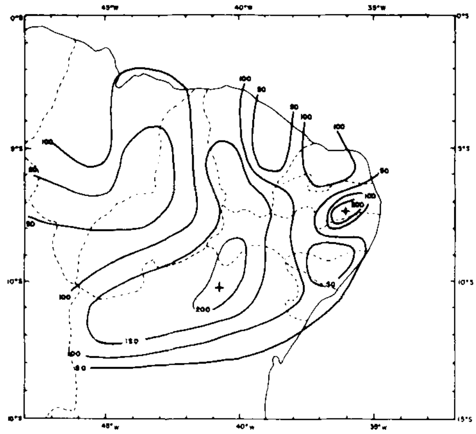

Fig. 4. Normalized deviations of rainfall for March–April–May of 1974.

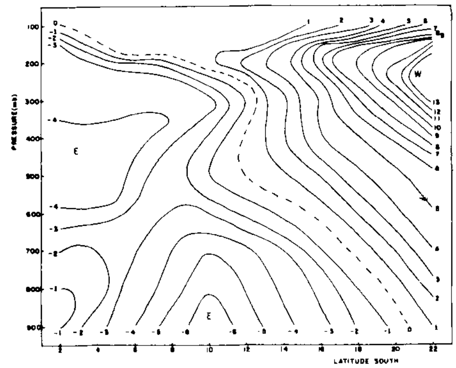

Fig. 6. Zonal wind component in a cross section along approximately 41° W, March–April–May 1974.

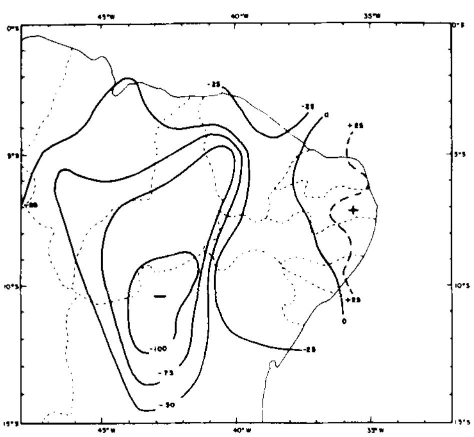

Fig. 5. Same as Fig. 4 but for 1976.

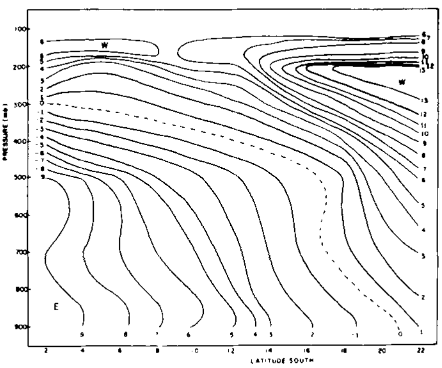

Fig. 7. Same as Fig. 6 but for 1976.

season for most of NE Brazil region. On the other hand, results obtained by Aldaz (1971) and Azevedo (1974) permit us to adopt September–October–November as the main dry season over NE Brazil. The differences in the atmospheric characteristics between these two 3-month periods are hereafter referred to as seasonal variations.

In order to study inter-annual variations, wet and dry years are selected. For this, rainfall data of 58 rain-gauge stations, which are uniformily distributed over NE Brazil, are examined for the same period for which upper air data are also available, namely 1971–78.

Initially, means and standard deviations for each station are determined for the 8-year period. Then, the departures of individual years are expressed in terms of the standard deviation producing normalized departures. All station averages of normalized departures are shown in Fig. 3. From this diagram it can be seen that 1974 is a year of high rainfall, and 1976 a dry year.

In order to examine the spatial distribution of rainfall for the dry and wet years, the deviation for the principal rainy season (March–April–May) from the normal is expressed as

$$D = \frac{p_i - \bar{p}}{\bar{p}} \times 100,$$

where D is the normalized deviation expressed in %, $\bar{p}$ is the normal, p_i is the precipitation for March–April–May of 1974 or 1976. The normalized deviations are obtained for each station and the isolines of these deviations are shown in Figs. 4 and 5. It can be seen that in 1974, most of

NE Brazil experienced heavy rainfall with deviations as much as 200% in the so-called drought polygon (see Ramos, 1975, for the definition of the drought polygon). During the year 1976, most of NE Brazil experienced lower rainfall with a small region having no rainfall. The positive deviation near the coast in Fig. 5 may be due to coastal effects such as land and sea breezes (Kousky, 1980).

In summary, we take March–April–May as the wet season, September–October–November as the dry season and 1974 and 1976 as the wet and dry years, respectively. The differences in atmospheric characteristics between wet and dry seasons are termed as seasonal differences, while the differences between the wet seasons of 1974 and 1976 are termed as inter-annual variations.

In the following, the zonal wind behaviour over NE Brazil is discussed. Zonal wind presents interesting differences in contrasting periods. Variations in the other directly measured meteorological variables are not that pronounced; they are given in Marques (1981).

4. Zonal wind behaviour over NE Brazil

Some of the earlier authors noted some difference in the behaviour of the surface winds over NE Brazil in contrasting years. For example Hastenrath and Heller (1977) noted a strengthening of trade winds in the dry years as compared to the wet years. Namias (1972), however, suggested a weakening of trades in the dry years. In this section we discuss the differences in the zonal wind behaviour, utilizing 8 years of upper air data. Figs 6 and 7 show the vertical section of zonal wind along the meridian 41°30′ W which passes approximately through the centre of the base of the cylinder, for the rainy seasons of 1974 and 1976, respectively. In both the years one can note easterlies (representative of SE trades) in the lower atmosphere and westerlies in the upper troposphere. Nevertheless, there are some clear quantitative differences. In the dry year 1976, the easterlies are stronger up to about 400 mb from the surface in the low latitudes. This is in agreement with that found by Hastenrath and Heller (1977) for the surface. The inclination of the zero line separating low-latitude trades from the westerlies of higher latitudes is related to the inclination of the subtropical high. The mean vertical sections for the wet and dry seasons of the 8-year period (not shown here) also show similar characteristics, although the differences are less pronounced.

The differences in the relative strength of tropical easterlies underlying westerlies seem to play an important rôle in determining the divergence and convergence patterns, which in turn will be decisive in creating the corresponding rainfall anomalies. These aspects are discussed in Section 7.

5. Atmospheric heat and energy balance equations

The equation of motion can be written in vector form in the pressure co-ordinates as

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathbb{V} = -\nabla\phi - fk \times \mathbb{V} + \mathbb{F}. \tag{1}$$

The thermodynamic equation can be written as

$$c_{\mathrm{p}}\frac{\mathrm{d}T}{\mathrm{d}t} = \dot{Q} + \omega\alpha. \tag{2}$$

The equation of continuity and the hydrostatic equation are, respectively

$$\nabla\cdot\mathbb{V} + \frac{\partial\omega}{\partial p} = 0, \tag{3}$$

$$\frac{\partial\phi}{\partial p} = -\alpha. \tag{4}$$

In eqs. (1)–(4), the symbols have their usual meaning. Taking the scalar product of (1) with $\mathbb{V}$ and using the continuity eq. (3) and also (4), we get the kinetic energy equation as

$$\frac{\partial}{\partial t}K + \nabla\cdot(K+\phi)\,\mathbb{V}$$

$$+\frac{\partial}{\partial p}(K+\phi)\,\omega + \omega\alpha = \mathbb{V}\cdot\mathbb{F} \tag{5}$$

where $K = \frac{1}{2}(u^2 + v^2)$, the kinetic energy.

Using the continuity equation, eq. (2) can be written as

$$\frac{\partial}{\partial t}C_{\mathrm{p}}T + \nabla\cdot C_{\mathrm{p}}T\mathbb{V} + \frac{\partial}{\partial p}C_{\mathrm{p}}T\omega - \omega\alpha = \dot{Q}. \tag{6}$$

Adding (5) and (6) we get the total energy equation as

$$\frac{\partial}{\partial t}(K + C_pT) + \nabla\cdot(K + \phi + C_pT)\mathbb{V}$$

$$+\frac{\partial}{\partial p}(K + \phi + C_pT)\,\omega = \dot{Q} + \mathbb{V}\cdot\mathbb{F}. \qquad (7)$$

Now integrating (7) and neglecting the local variations in time, the frictional term and the third term on the left-hand side, we get

$$\int\int\int \nabla\cdot(K + \phi + C_pT)\mathbb{V}\,dm = \int\int\int \dot{Q}\,dm, \qquad (8)$$

where dm is a mass element.

Some comments are in order regarding the vertical flux term. Although the integral of $(\partial/\partial p)$ $(K + \phi)\,\omega$ is probably small, the integral of $(\partial/\partial p)$ ωC_pT may not be negligible. The value of $C_pT\omega$ at the lower boundary could be large. Some discussion on the importance of this term was given by Hantell and Baader (1978). However, this term can be taken over to the right-hand side, to join with sensible heat component of $\dot{Q}$. In eq. (8), the kinetic energy is small in comparison with other terms and is also neglected.

We propose to evaluate (8) for a cylindrical mass of the atmosphere over NE Brazil as mentioned earlier. For this purpose we write (8) applying the divergence theorem, as

$$\dot{H} = \int\int\int \dot{Q}\,dm = \int\int (C_pT + \phi)\,V_n\,d\sigma, \qquad (9)$$

where V_n is the component of wind normal to the boundary (positive outward) and $d\sigma$ is an element of the area of lateral surface of the cylinder; $d\sigma = R d\xi dp/g$, where R is the radius of the cylinder (600 km) and $d\xi$ the azimuthal angle.

The left-hand side heating term can be divided into 3 components, namely, H_S the sensible heating, H_L the latent heating and H_R the net radiational cooling, i.e.,

$$H_S + H_L - H_R = \frac{R}{g} \times \oint\int_{p_T}^{p_0}(C_pT + \phi)\,V_n\,d\xi\,dp, \qquad (10)$$

where P_T is 100 mb and P_0 is the surface pressure.

Now H_L can be written as

$$H_L = LP = LE - \frac{R}{g}\oint\int_{p_T}^{p_0} LqV_n\,d\xi\,dp. \qquad (11)$$

Here P_T is taken as 300 mb. In (11), L, P, E are the heat of condensation, and rates of precipitation and evaporation, respectively. With (11), (10) can be written as

$$H_S - H_R + LE = \frac{R}{g}\oint\int_{p_T}^{p_0}(C_pT + \phi Lq)\,V_n\,d\xi\,dp. \qquad (12)$$

In (12), $(C_pT + \phi + Lq)$ is called the moist static energy. The total mass flux is given by

$$FLM = \frac{1}{g}\oint\int_{p_T}^{p_0} RV_n\,d\xi\,dp. \qquad (13)$$

The flux integrals of (10) and (11) can be broken up into contributions of mean and eddy motions. The eddy motions can be partly due to variations of wind and other parameters around the boundary (space eddy terms), and partly due to variations in time. Since the present study is based on monthly mean data, time eddy terms of shorter duration are omitted and eddy terms refer to space eddies only. From now on let us refer to $(C_pT + \phi)$ as sensible heat. Thus the sensible heat and latent heat flux terms in (10) and (11), when broken into mean and eddy terms, can be written as

$$H = \frac{R}{g}\oint\int_{p_T}^{p_0}\overline{(C_pT + \phi)}\,\bar{V}_n\,d\xi\,dp + \frac{R}{g}\oint\int_{p_T}^{p_0}\overline{(C_pT + \phi)'\,V_n'}\,d\xi\,dp, \qquad (14)$$

$$H_L = \frac{R}{g}\oint\int_{p_T}^{p_0}\bar{q}\bar{V}_n\,d\xi\,dp + \frac{R}{g}\oint\int_{p_T}^{p_0}\overline{q'V_n'}\,d\xi\,dp. \qquad (15)$$

In (14) and (15) bars and primes represent mean and eddy terms respectively.

6. Evaluation of heat content of a cylinder over NE Brazil

The lateral surface of the cylinder is divided into a grid having 9 points in the horizontal with an equal separation of 400 km, and 9 points in the

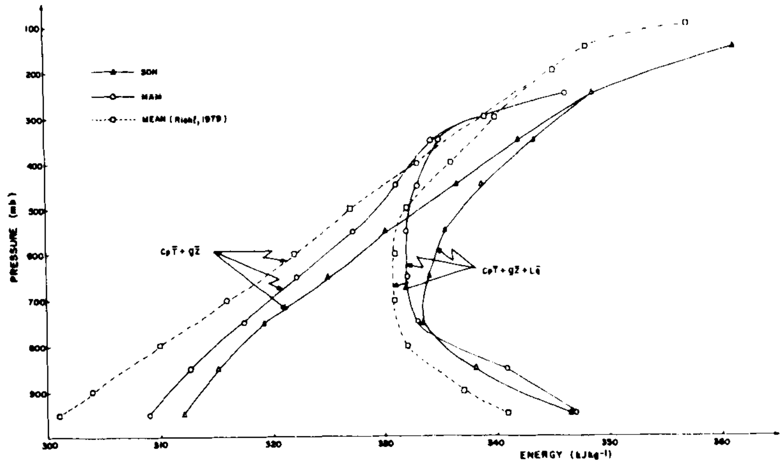

Fig. 8. Vertical profiles of $(C_p\bar{T} + \bar{\phi})$ and $(C_p\bar{T} + \bar{\phi} + L\bar{q})$ averaged around the lateral boundary of the cylinder, for the wet and dry seasons (kJ kg^{-1}).

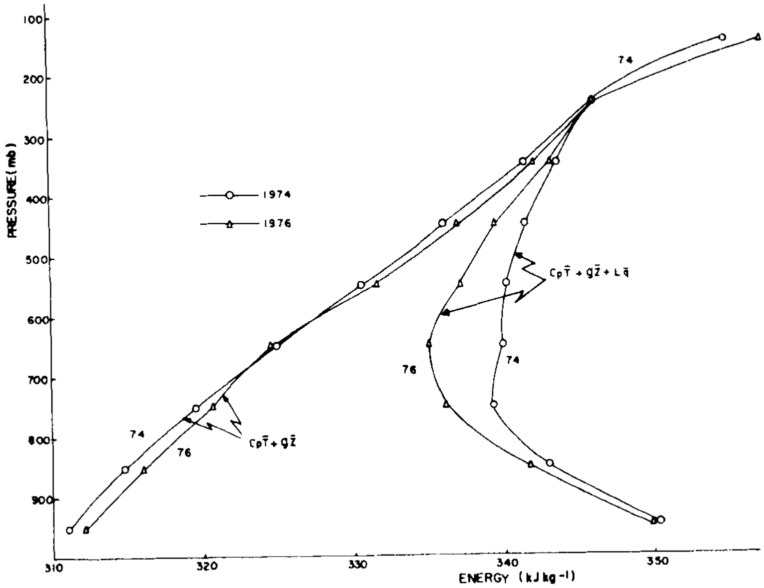

Fig. 9. Same as Fig. 8 but for the wet seasons of 1974 and 1976.

vertical with an equal separation of 100 mb from surface to 100 mb. As mentioned earlier, all data are checked for consistency at each station by plotting vertical profiles. The vertical space sections are prepared for each element with pressure on a linear scale as the ordinate, and the peripheral distance as abscissae. After the space section analysis, data are picked up at the 9 grid points for each of the 9 levels. These 9 values are averaged horizontally to yield the mean values around the cylinder for each layer.

Tables 1a, b, c and d show the values of the energy content for the 4 different cases mentioned in Section 3. The first two cases shown in Fig. 8 represent seasonal variations while the latter two in Fig. 9 indicate inter-annual variations.

Table 1. *Mean energy of the atmosphere over northeast Brazil* ($kJ\ kg^{-1}$). (a) *For March–April–May, 8 years (1971–78) mean.* (b) *For September–October–November, 8 years (71–78) mean.* (c) *For March–April–May of 1974.* (d) *For March–April–May of 1976*

(a)

Pressure (mb)	$C_p\bar{T}$	$\bar{\phi}$	$L\bar{q}$	$C_p\bar{T}+\bar{\phi}$	$C_p\bar{T}+\bar{\phi}+L\bar{q}$
Surface–900	294.8	14.2	37.8	309.0	346.8
900–800	289.2	23.5	28.3	312.7	341.0
800–700	283.7	33.8	15.6	317.5	333.1
700–600	276.9	45.3	9.9	322.2	332.1
600–500	268.9	58.4	4.8	327.3	332.1
500–400	257.6	73.5	2.5	331.1	333.6
400–300	242.9	91.4	0.6	334.3	334.9
300–200	232.6	113.7		346.3	346.3
200–100	196.5	144.8		341.3	341.3

(b)

Pressure (mb)	$C_p\bar{T}$	$\bar{\phi}$	$L\bar{q}$	$C_p\bar{T}+\bar{\phi}$	$C_p\bar{T}+\bar{\phi}+L\bar{q}$
Surface–900	298.0	14.2	34.7	312.2	346.9
900–800	291.7	23.5	23.1	315.2	338.3
800–700	285.9	33.8	13.8	319.7	333.5
700–600	279.8	45.2	9.2	325.0	334.2
600–500	272.7	58.2	4.6	330.9	335.5
500–400	263.6	73.3	2.0	336.9	338.9
400–300	251.2	91.2	0.8	342.4	343.2
300–200	235.2	113.6		348.8	348.8
200–100	216.5	114.8		331.3	331.3

(c)

Pressure (mb)	$C_p\bar{T}$	$\bar{\phi}$	$L\bar{q}$	$C_p\bar{T}+\bar{\phi}$	$C_p\bar{T}+\bar{\phi}+L\bar{q}$
Surface–900	297.0	14.2	39.2	311.2	350.4
900–800	291.3	23.5	28.3	314.8	343.1
800–700	285.9	33.7	19.9	319.6	339.5
700–600	279.8	45.2	15.2	325.0	340.2
600–500	272.4	58.3	9.7	330.7	340.4
500–400	263.0	73.3	5.3	336.3	341.6
400–300	250.3	91.4	2.2	341.7	343.9
300–200	232.6	113.6	—	346.2	346.2
200–100	211.7	143.8	—	355.5	355.5

(d)

Pressure (mb)	$C_p\bar{T}$	$\bar{\phi}$	$L\bar{q}$	$C_p\bar{T}+\bar{\phi}$	$C_p\bar{T}+\bar{\phi}+L\bar{q}$
Surface–900	297.9	14.2	37.9	312.1	350.0
900–800	292.5	23.5	25.8	316.0	341.8
800–700	286.9	33.8	15.5	320.7	336.2
700–600	279.3	45.3	10.5	324.6	335.1
600–500	273.4	58.4	5.7	331.8	337.5
500–400	263.6	73.5	2.6	337.1	339.7
400–300	250.8	91.5	1.2	342.3	343.5
300–200	232.7	113.7		346.4	346.4
200–100	214.7	114.1		328.8	328.8

It can be seen that in all the cases $\overline{(C_p T + \phi)}$ increases with height while $\overline{(C_p T + \phi + Lq)}$ has a minimum in the lower troposphere with higher values both in the lowest levels and in the upper troposphere. These are some of the well-known qualitative characteristics of the tropical atmosphere (Riehl, 1979). However, there are clear quantitative differences. From Fig. 8 it can be seen that both the total energy and sensible heat energy values over NE Brazil below 500 mb in both the seasons are higher than the corresponding values for the mean equatorial trough zone as given by Riehl. Furthermore, Fig. 8 shows the differences between the dry and wet seasons. The sensible heat energy is larger at all levels during the dry season compared to the wet season, while the total energy is larger at high levels but somewhat smaller at low levels. In addition, the vertical gradient during the wet season is higher at lower levels. Another interesting feature of the total energy during the wet season is the layer of more-or-less constant values in the middle troposphere from about 800 mb up to 500 mb. A somewhat similar feature is also seen in Riehl's values for the equatorial trough zone. It is known that during the wet season the equatorial trough is closer to NE Brazil (Hastenrath and Heller, 1977). The implications of the structure of the profiles for the development of convection have already been discussed by Riehl (1979).

Regarding the inter-annual variability (Fig. 9), the profiles of sensible heat energy are not much different. Nevertheless, the total energy profiles show clear differences. The humidity values are higher during the wet year. More interestingly, the shapes of dry and wet profiles are somewhat reminiscent of the dry and wet seasons respectively, although the relative magnitudes differ. This again is consistent with the earlier findings (Hastenrath and Heller, 1977), namely, that the equatorial trough zone is closer to NE Brazil in the wet years than in the dry years.

7. Normal component of velocity

Figs. 10 and 11 show the normal component of velocity for the 4 cases. These values are adjusted for mass conservation. In these figures, the original unadjusted values are also shown. Since the normal velocities (V_n) are calculated for each 100 mb layer, the conservation of mass is given simply by the requirement that the sum of normal velocities be zero. The adjustment required was small. The normal velocity can also be converted into average divergence using the formula $D = (S/A)\, V_n$, where S is the circumference of the circle (3.77×10^3 km) and A is the area of the circle (11.31×10^5 km^2). Thus $S/A = 3.3 \times 10^6$ m^{-1}.

In view of the small values of V_n, an error analysis was performed. The method used is similar to that used earlier by Fuelberg and Scoggins (1980) and Ward and Smith (1976). We used the probable errors in the direction and speed of the wind furnished by Kurihara (1961). The error bars in V_n for the arbitrarily chosen mean (1971–78) March, April and May case are shown in Fig. 12. It can be seen that the error bars are rather large at higher levels. However, as the error bars are obtained for each level independently, the possibility of V_n assuming high or low values simultaneously is less. Thus, the normal velocities are reasonable, taking into consideration the presently available accuracy in the wind measurement.

It is seen from Figs. 10 and 11 that during the wet period, there is an inward mass flux (V_n negative) in the lower levels and an outward mass flux in the upper levels. During the dry period, there is an inward mass flux in the middle levels with an outward mass flux above and below.

In the tropics, the observed total rainfall is the result of a few rain episodes and not due to rainfall on all the days of the rainy season (Riehl, 1979). Thus the mean conditions of the atmosphere which are favorable or unfavorable for the occurence of rain episodes are decisive for excess or deficit rainfall.

Over NE Brazil during the dry periods, convergence in the middle levels forcing a subsidence in the lower levels seems to be the mechanism which inhibits the development of clouds and precipitation. On the other hand, during the wet periods, convergence in low levels and divergence in upper levels favor the development of clouds and precipitation. The discussion in the previous sections suggests that favorable or unfavorable conditions for precipitation are clearly linked to general circulation features, such as the location of the ITCZ.

8. Heat and moisture fluxes

The sensible heat and latent heat fluxes around the boundary have been evaluated using eqs. (14)

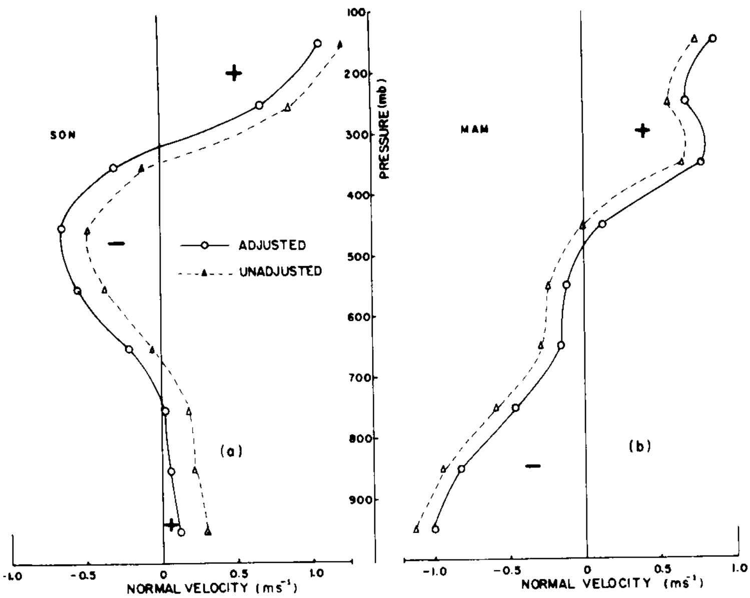

Fig. 10. Vertical profile of the component of wind normal to the boundary of the cylinder for the wet and dry seasons; negative values indicate inward component.

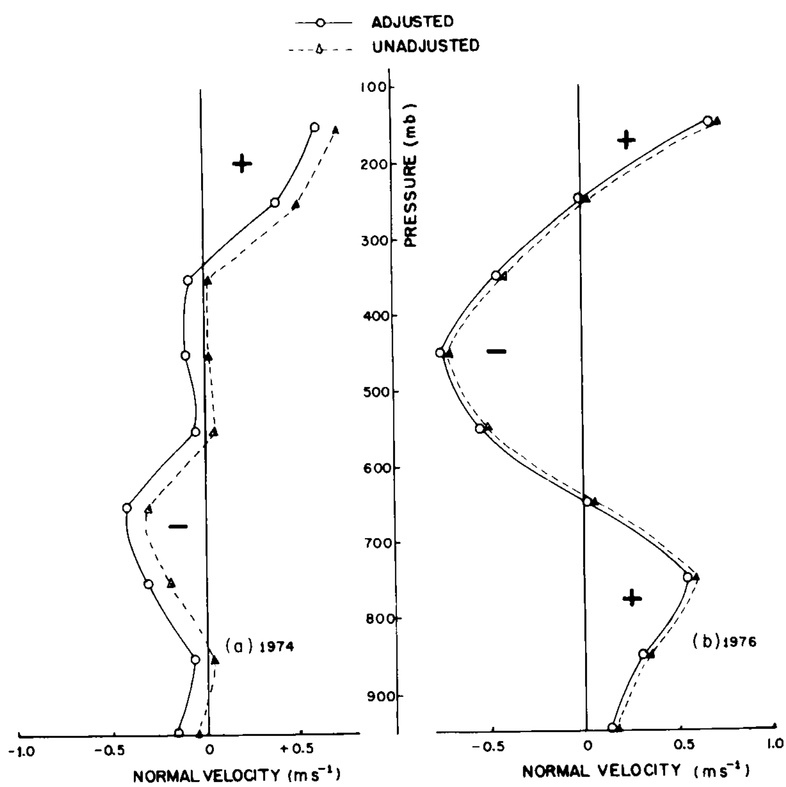

Fig. 11. Same as Fig. 10 but for the wet seasons of 1974 and 1976.

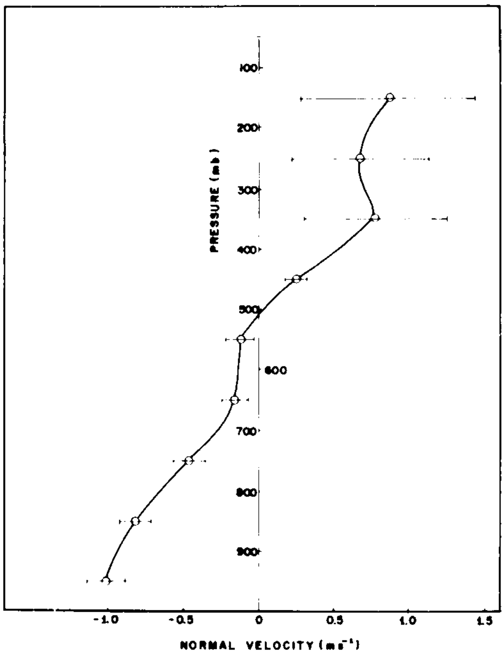

Fig. 12. Vertical profile of normal velocity and error standard deviations at various levels.

and (15). Tables 2a, b and c show the fluxes of $(C_p\bar{T} + \bar{\phi})$, $L\bar{q}$ and $C_p\bar{T} + \bar{\phi} + L\bar{q}$, respectively, for the dry and wet seasons. Similarly Tables 3a, b and c show the fluxes for the dry and wet years.

Tables 2 show that during the wet season there is a large import of sensible heat at lower levels and export at higher levels, and during the dry season there is import in the middle levels with export in the low and high levels. Eddies seem to play a minor rôle. Water vapor flux is negative (inward) and large at lower levels in the wet season and this is mostly accomplished by mean motions. During the wet season, there is a net import of 21.37×10^{13} Js^{-1}. During the dry season the quantities are comparatively small at all levels, and there is a net export of 5.02×10^{13} Js^{-1}.

Regarding the inter-annual variations, during the wet year 1974, there was import of sensible heat at all levels except the top two levels. During the dry year 1976, there was export at lower levels and import at higher levels, and again import at the top-most level. Although, there is a small net export in both the years, the import and export values at different levels are larger in 1976. Here again the eddies seem to play a minor rôle. The main difference is found in the water vapour flux. During the wet year, there is import at the lower levels and export at higher levels, amounting to a net import of 6.0×10^{13} Js^{-1}. During the dry year, there is a large export of water vapour at lower levels resulting in a net export of 11.24×10^{13} Js^{-1}.

9. Summary and conclusions

Inter-annual and seasonal variations of climate over NE Brazil are discussed. Differences between the principal rainy season, March, April and May, and the dry season September, October and November are termed as seasonal differences. On the other hand, differences between the rainy season of the wet year 1976 and the rainy season of the dry year 1974 are denominated as inter-annual differences.

Analysis of zonal wind over a meridian which passes through the middle of the NE Brazil dry region showed that easterlies between 2°–10° S become weak during the wet period in the lower latitudes. Calculation of the normal wind component for a cylindrical area containing NE Brazil indicated changes in the direction of mass flux at lower levels between the dry and wet periods. The occurrence of influx of mass at lower levels during the wet period and the outflux during the dry period, together with an error analysis of the normal component of velocity showed that its determination is reliable.

An examination of vertical profiles of $(C_p\bar{T} + \bar{\phi} + \bar{q})$ for the 4 periods showed that the vertical structure of this quantity during the wet period is similar to that found for the equatorial trough region. This, along with the fact that the equatorial trough is closer to NE Brazil during the wet period, suggests the important rôle of the equatorial trough in the variations of rainfall over NE Brazil. The proximity of the equatorial trough during a wet period is also connected with the above-mentioned weakening of easterlies. This weakening of easterlies is in turn associated with the structure of the normal component of velocity favorable for precipitation. Thus, it seems that the rainfall variations in NE Brazil are not of local origin but are connected with the variations of the general circulation in the tropics. Clearly, the variations in the location of the equatorial trough

Table 2. *Seasonal variation of lateral fluxes of energy by mean and eddy motions. 8 year means* (10^{13} Js^{-1}). (a) *Flux of* $(C_p\bar{T} + \bar{\phi})$. (b) *Flux of* $(L\bar{q})$. (c) *Flux of* $(C_p\bar{T} + \bar{\phi} + L\bar{q})$

(a)

Pressure (mb)	Mean		Eddy		Total	
	MAM	SON	MAM	SON	MAM	SON
Surface–900	−226.2	+26.3	+0.2	−0.1	−226.0	+26.2
900–800	−185.0	+13.1	+0.2	+0.6	−184.8	+13.7
800–700	−105.5	+2.5	+0.1	+0.2	−105.4	+2.7
700–600	−37.5	−48.2	+0.1	−0.2	−37.4	−48.4
600–500	−27.5	−128.1	+0.1	−0.1	−27.4	−128.2
500–400	+57.7	−152.6	+0.2	+0.1	+57.9	−152.5
400–300	+189.9	−74.4	+0.2	−0.1	+190.1	−74.5
300–200	+162.7	+109.5	−2.8	−1.4	+159.9	+108.1
200–100	+206.1	+260.4	+0.4	−1.0	+206.5	+259.4
Total	+34.7	+8.5	−1.3	−2.0	+33.4	+6.5

(b)

Pressure (mb)	Mean		Eddy		Total	
	MAM	SON	MAM	SON	MAM	SON
Surface–900	−14.7	+1.6	−1.5	−0.9	−16.2	+0.7
900–800	−9.0	+0.5	+1.5	+1.5	−7.5	+2.0
800–700	−2.8	+0.1	+2.2	+2.4	−0.6	+2.5
700–600	−0.6	−0.7	+1.6	+1.5	+1.0	+0.8
600–500	−0.2	−1.0	+1.2	+0.6	+1.0	−0.4
500–400	+0.2	−0.5	+0.4	+0.2	+0.6	−0.3
400–300	+0.2	−0.1	—	—	+0.2	−0.1
300–200	—	—	—	—		
200–100	—	—	—	—		
Total	−26.9	−0.1	+5.4	+5.3	−21.5	+5.2

(c)

Pressure (mb)	Mean		Eddy		Total	
	MAM	SON	MAM	SON	MAM	SON
Surface–900	−240.9	+27.9	−1.3	−1.0	−242.2	+26.9
900–800	−194.0	+13.6	+1.7	+2.1	−192.3	+15.7
800–700	−108.3	+2.6	+2.3	+2.6	−106.0	+5.2
700–600	−38.1	−48.9	+1.7	+1.3	−36.4	−47.6
600–500	−27.7	−129.1	+1.3	+0.5	−26.4	−128.6
500–400	+57.9	−153.1	+0.6	+0.3	+58.5	−152.8
400–300	+190.1	−74.5	+0.2	−0.1	+190.3	−74.6
300–200	+162.7	+109.5	−2.8	−1.4	+159.9	+108.1
200–100	+206.1	+260.4	+0.4	−1.0	+206.5	+259.4
Total	+7.8	+8.4	+4.1	+3.3	+11.9	+11.7

Table 3. *Inter-annual variations of lateral fluxes of energy by mean and eddy motions* (10^{13} Js^{-1}). (a) *Flux of* $(C_p\bar{T} + \bar{\phi})$. (b) *Flux of* $(L\bar{q})$. (c) *Flux of* $(C_p\bar{T} + \bar{\phi} + L\bar{q})$

(a)

Pressure (mb)	Mean		Eddy		Total	
	1974	1976	1974	1976	1974	1976
Surface–900	−35.6	+29.6	−1.2	+0.1	−36.8	+29.7
900–800	−13.1	+69.9	−0.8	+0.1	−13.9	+70.0
800–700	−69.1	+124.2	−0.4	−0.2	−69.5	+124.0
700–600	−97.9	+6.9	−0.3	+0.2	−98.2	+7.1
600–500	−10.9	−127.8	−0.1	−0.5	−1.0	−128.3
500–400	−24.0	−154.2	+0.2	−0.4	−23.8	−154.6
400–300	−21.6	−107.0	+0.3	+0.3	−21.3	−106.7
300–200	+116.2	−5.6	+0.7	+0.7	+116.9	−4.9
200–100	+166.4	+167.0	−0.7	+3.7	+165.7	+170.7
Total	+10.4	+3.0	−2.3	+4.0	+8.1	+7.0

(b)

Pressure (mb)	Mean		Eddy		Total	
	1974	1976	1974	1976	1974	1976
Surface–900	−2.4	+1.9	−1.0	+1.0	−3.4	+2.9
900–800	−0.6	+3.1	+0.1	+0.6	−0.5	+3.7
800–700	−2.3	+3.2	+0.5	+1.2	−1.8	+4.4
700–600	−2.5	+0.1	+0.6	+1.0	−1.9	+1.1
600–500	−0.2	−1.2	+0.8	+0.8	+0.6	−0.4
500–400	−0.2	−0.7	+0.8	+0.3	+0.6	−0.4
400–300	−0.1	−0.2	+0.4	+0.1	+0.3	−0.1
300–200						
200–100						
Total	−8.3	+6.2	+2.2	+5.0	−6.1	+11.2

(c)

Pressure (mb)	Mean		Eddy		Total	
	1974	1976	1974	1976	1974	1976
Surface–900	−38.0	+31.5	−2.2	+1.1	−40.2	+32.6
900–800	−13.7	+73.0	−0.7	+0.7	−14.4	+73.7
800–700	−71.4	+127.4	+0.1	+1.0	−71.3	+128.4
700–600	−100.4	+7.0	+0.3	+1.2	−100.1	+8.2
600–500	−11.1	−129.0	+0.7	+0.3	−10.4	−128.7
500–400	−24.2	−154.9	+1.0	−0.1	−23.2	−155.0
400–300	−21.7	−107.2	+0.7	+0.4	−21.0	−106.8
300–200	+116.2	−5.6	+0.7	+0.7	+116.9	−4.9
200–100	+166.4	+167.0	−0.7	+3.7	+165.7	+170.7
Total	+2.1	+9.2	−0.1	+9.0	+2.0	+18.2

are connected with other aspects of the general atmospheric and oceanic circulation; an examination of these aspects is beyond the scope of this paper.

Water vapor flux calculations showed that during the wet period there is a net import of water vapor, and during the dry period a net export. During the dry year 1976, a net export of latent heat amounting to 11.24×10^{13} Js^{-1} occurred. Considering the cylindrical area as 11.31×10^{15} cm^2, this corresponds to an excess of evaporation over precipitation of about 4 mm day^{-1}. Since the rainfall in this region occurs mainly in the months of March, April and May (for which the calculations are made), the water vapor loss of this order should be considered serious. During the wet year 1974, the import of water vapor was only 6.0×10^{13} Js^{-1}, which corresponds to an excess of precipitation over evaporation of about 2.1 mm day^{-1}. This again shows that even during a heavy rainfall year, the evaporation rate is high such that the water availability in the soil during the rest of the year is small.

In the present study, however, only monthly mean values are used. It would be worthwhile to extend this study using daily data.

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