Precipitable water and water vapor flux between Belém and Manaus(*)

José Marques (1)
Jesus Marden dos Santos (2)
Nilson Augusto Villa Nova (2)
Eneas Salati (3)

Abstract

The water vapor flux and precipitable water was computated over the natural Amazon forest in the stretch between Belem and Manaus for 1972. The atmospheric branch of hidrological cycle teory was applied and the most significant conclusions on an annual basis are: Atlantic Ocean water vapor contributes 52% to the regional precipitation and is significant the role played by local evapotranspiration in the precipitation in the area; there were signs of the phenomenon of water vapor recycling nearly throughout the year. Evapotranspiration contribute to 48% of the precipitations in the area studied. The real evapotranspiration estimated by this method was 1,000mm year^{-1}.

INTRODUCTION

From the beginning, the establishment of agro-industrial projects on a large scale in the Amazon Region has caused doubts as to the possible ecological modifications in this region as a consequence of replacing the equatorial forest by other types of vegetation.

On the probable changes, two are of importance as they can induce other ecological adaptations: a) quantitative variations in the components of the hydrologic cycle; b) qualitative and quantitative alterations in the cycle of nutrients.

The basic problem in the hydrologic cycle is to determine whether the water vapor from the evapotranspiration is a relevant factor in the water economy of this region with approximately 6 million square kilometers and which contains 20% of the earth's fresh water reserve.

The present paper is a contribution to the study of the problem of characterizing the two components which constitute the atmospheric branch of the hydrologic cycle, namely, the water vapor flux (zonal and meridional) and the precipitable water, as detected over the Amazon natural forest in the stretch between Belém and Manaus. It attempts to:

a) asses the volume of precipitable water over Manaus and Belem, and determine its monthly variation;

b) asses the total water vapor flux over these locations, the zonal flux available between them, and determine its monthly variations;

c) establish a correlation between the precipitable water, the zonal and meridional components of the water vapor flux, the potential evapotranspiration and the rainfall in the region, with a view to providing evidence of a possible water vapor recycling in the region.

LITERATURE REVIEW

The use of information of the upper air to determine the water content over a location and to calculate the water vapour flux divergence over a region, provided two or more observing stations are available, was initiated by the work of Holzman (1937). As from the equation of state for humid air, a method was established to estimate the water content in the atmospheric layer as a function of vapor pressure, of air temperature and of height Z. According to Barnes (1964), the first scientists to make calculations of atmospheric water vapor divergence were Wundt in 1938, in very restricted areas, and later Benton *et al.* (1950). Peixoto (1968) characterizes the hydrologic cycle as having two equivalent branches: one terrestrial and one atmospheric, concluding that the

(*) — Work carried out with the support of CNEN and FAPESP (Física 73/479).
(1) — Dept. of Meteorology — I. Geociências, UFRJ, Rio de Janeiro, RJ.
(2) — Escola Superior de Agricultura "Luiz de Queiroz", USP, Piracicaba, SP.
(3) — Centro de Energia Nuclear na Agricultura, Piracicaba, SP.

balances of the water component, carried out by study of the atmospheric branch, are the most accurate, provided a reasonable network system is available for observations of altitude. Due to the complex relationship between evaporation and air temperature, wind intensity and direction and precipitation characteristics, and soils and vegetation types, it has not been possible to estimate accurately by means of conventional methods the water volume evaporated from large drainage basins. The study of the atmospheric branch of the hydrologic cycle overcomes this difficulty, for it introduces in a relatively easy manner concepts with well-defined and measurable physical significance.

Molion (1975), in a study of the components of the equations of water balance and energy balance, presented possible climatic effects from deforestation of the Amazon Basin; he utilized average charts of wind and specific humidity seasonal values published by Newell *et al.* (1972).

McDonald (1962) showed the scientific uncertainity of accepting the "in-situ" evaporation — precipitation process, for the water vapor molecules supplied to the air are transported by atmospheric circulation from the site of origin to up to hundreds of kilometers, before they are condensed and precipitate. Only in some specific cases, as for instance on abruptly rising land near an extensive liquid surface, can there be substantial effects of the local liquid mass over precipitation.

In a study of the water balance of the Mississipe River Basin, Benton, as cited by McDonald (1962), included that not more than 10% of the precipitation in the area consisted of water evaporated from local continental sources, the remaining 90% being of marine origin. For the Amazonas Basin, however, Molion (1975) concluded that about half of the precipitation consists of local evapotranspirated water.

The main limitations of the method are:

— it disregards the total water transported in the solid and liquid phases. In some specific cases in synoptic studies for restricted areas, the water in the clouds may represent a considerable part of the total humidity transported. For large areas, and using mean water vapor flux divergence values for lengthy time periods, the water in the clouds can be negligible. Sometimes in these cases there may exist regions where the strong orographic influence and proximity to large liquid masses induce condensation and systematic errors can originate from this source.

— if the aerological observations are carried out only once a day, the results can be heavily influenced by a possible daily variation of the wind and/or the specific humidity.

— computing the water vapor flux in an extensive region over a lengthy period, it is necessary that the total number of observations be equal for all the stations.

— the method can be successfully utilized only in regions where a closely spaced network of aerological stations exist.

Data

The surface meteorological data utilized were: the records of totals of precipitation and air temperature from the stations of the Ministério da Aeronáutica and Ministério da Agricultura, and of the Instituto Nacional de Pesquisas da Amazônia (INPA), during 1972.

The necessary data for water vapor fluxes and precipitable water computations were determined from the analysis of 658 daily meteorological upper air observations (radiosonde) carried out in 1972 by the Ministério da Aeronautica at its stations in Manaus and Belem.

As this study was carried out with data for only one year, the conclusions are subject to the statistical oscilations pertinent to the meteorological data. As will be seen, this year yielded meteorological data considered to be within the normals established for the region. Fig. 1 shows the localization of studied area.

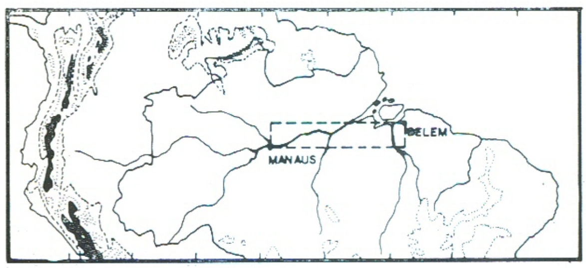

Fig. 1 — (Topographic map and localization of the area under study, dashed line 500m level dotted area 1000 to 2000m blackened area over 2000m).

METHODS

Precipitable water (Wp)

Precipitable water (Wp) is, by definition, "the total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between any two specified levels, commonly expressed in terms of the height to wich that water substance would stand if completely condensed and collected in a vessel of the same unit cross-section".

In the present work, the method proposed by Harrison (1970) has been adopted for calculating Wp, the precipitable water (in mm) being determined from the expression:

$$Wp = \frac{10}{g} \int_{Po}^{P} \bar{q} dP \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where

$\bar{q}$ — mean specific humidity, in grams of water vapor per kilogram of humid air.

P, Po — pressures of the isobaric surfaces bounded by the layer under study. expressed in mb.

g — acceleration of gravity, in ms^{-2}.

WATER VAPOR FLUX $\vec{Q}$

To estimate the water vapor flux $\vec{Q}$, the following general expression was utilized:

$$\vec{Q} = \frac{1}{g} \int_{Po}^{P} \bar{q}\vec{V} dP \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

broken down into its zonal (Q_λ) and meridional (Q_ϕ) components:

$$Q_\lambda = \frac{1}{g} \int_{Po}^{P} \overline{qu} dP \quad \ldots\ldots\ldots\ldots\ldots \quad (3);$$

and

$$Q_\phi = \frac{1}{g} \int_{Po}^{P} \overline{qv} dP \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

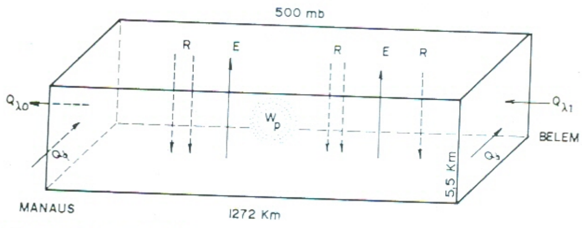

Fig. 2 — Model utilized for characterization of the components of the atmospheric branch of the hidrologic cycle.

where

Q_λ and Q_ϕ are expressed in $g\ cm^{-1}\ s^{-1}$;

$\underline{u}$ and $\underline{v}$ are, respectively, the wind's zonal and meridional components. Taken as positive are the $\underline{u}$ eastward values and $\underline{v}$ northward values, expressed in ms^{-1}.

In all the cases studied, use has made of the hydrostatic equilibrium condition in the atmospheric column, which was bounded by the isobaric standards levels 1,000 and 500mb.

MEAN PRECIPITATION ($\bar{R}$)

The mean precipitation ($\bar{R}$) utilized was determined for the rectangle formed by the intersections of the parallels and meridians of Belem and Manaus (Fig. 3).

MEAN "ADVECTIVE" ($\bar{R}a$)

By means of subtraction between the monthly water vapor zonal flux in Belem ($Q_{\lambda i}$) and Manaus ($Q_{\lambda o}$), the total water vapor for the precipitation processes can thus be found:

$$\Delta Q_\lambda = Q_{\lambda i} - Q_{\lambda o} \quad \ldots\ldots\ldots\ldots \quad (5)$$

Starting from ΔQ_λ, it was possible to estimate the fraction of local precipitation derived from the transport of water vapor to the region under study. In this paper, this fraction is called "advective rain" $\bar{R}a$, calculated by the expression:

$$\bar{R}a = 6{,}79 \times 10^{-3} \times t \times \Delta Q_\lambda \quad \ldots\ldots \quad (6)$$

where

t — time interval, during one month, expressed in seconds;

ΔQ_λ — is expressed in $g\ cm^{-1}\ s^{-1}$;

$\bar{R}a$ — is expressed in mm $month^{-1}$.

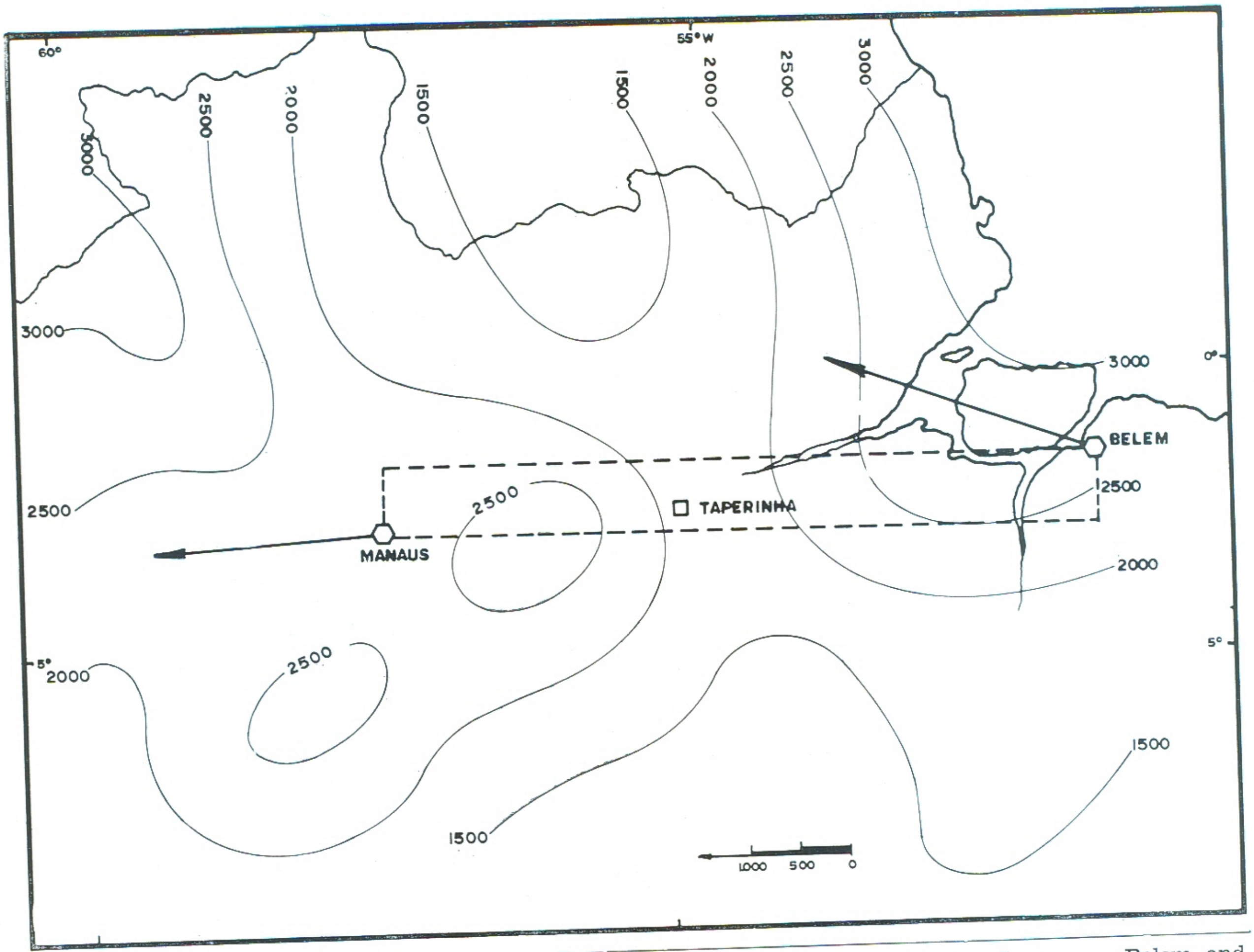

Fig. 3 — Total precipitation (in mm) in 1972. The arrows indicate the total vapor flux over Belem and Manaus (1cm = 500g/cm.s).

MEAN POTENTIAL EVAPOTRANSPIRATION ($\bar{E}$)

The mean potential evapotranspiration ($\bar{E}$) was determined from the available data on air temperature in Belem, Manaus and Taperinha by the method of Thornthwaite and Mather (1955).

THE MODEL

The model utilized for the characterization of some components of the atmospheric branch of the hydrologic cycle in the stretch extending from Belem to Manaus, consisted of a hypothetical volume (Fig. 2) taken from the atmosphere, 178km in width (approximately 1°40') and of a height corresponding to the standards isobaric level of 500mb (5,500m as an average), and whose length is the distance between those two towns, approximately 1,272km (11°33').

Due to the rapid vertical decrease in the specific humidity (q), it is not necessary to extend the integration to the top of the atmosphere; a large portion of the humidity total flow occurs in the layer between the surface and/or 400/500mb, Palmén (1967). In the present paper, the values computed for the levels above 500mb have not been considered.

RESULTS OBTAINED AND DISCUSSION

THE MEAN PRECIPITATION FIELD ($\bar{R}$)

From the precipitation data, the monthly isohyets were drawn and from these, the values were calculated from the mean rain $\bar{R}$ in the area under study, delimitated as indicated in the method for "Mean Precipitation ($\bar{R}$)". Utilizing the values for the variation coefficients determined by Azevedo (1974) and applying the "t Test", it was observed that the monthly values for rain which occurred in 1972 were not statistically different from the normal values established for Belem and Manaus. Fig. 3 shows the distribution of total precipitation in 1972 and fig. 6 shows its monthly variation.

MEAN PRECIPITABLE WATER (Wp)

The analysis of Fig. 4, constructed from the data in Table I, shows for Belem a main minimum in October and a secondary minimum in June and for Manaus a main maximum in April and two secondary maxima in December and August. A rough analysis shows that Belem gives values which are always lower than those observed for Manaus.

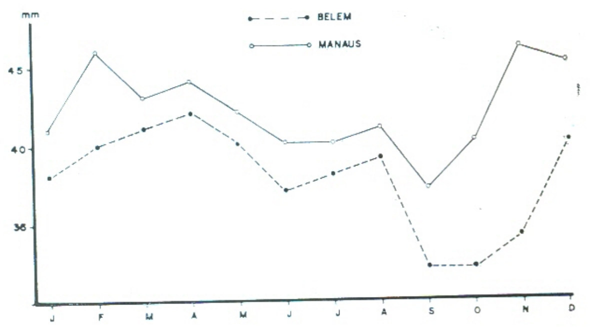

Fig. 4 — Monthly values of precipitable water (Wp) for 1972.

MEAN WATER VAPOR FLUX ($\overline{Q}$)

The zonal and meridional water vapor fluxes are shown in Table I and Fig. 5. It was observed that the total zonal flux at Belem was 430/cm higher than at Manaus, and that for both locations it kept the same direction, i.e., westward. The meridional flow at Belem indicated a constant northward direction, while at Manaus it was altemate, being from the south during the period April-September, and from the north during the remaining months. The total flux Q was constructed from the components $Q\lambda$ and $Q\phi$ of the flux, as shown in fig. 3.

MEAN ADVECTIVE RAIN ($\overline{Ra}$)

The $\overline{Ra}$ values, equation 6, are indicated in Table I and Fig 6.

MEAN POTENTIAL EVAPOTRANSPIRATION (E)

The values obtained by applying the Thornthwaite's method did not differ significantly from those found by Villa Nova et al. (1976), applying the Penman formula adapted for forests.

WATER BALANCE IN THE ATMOSPHERE

Peixoto (1968) demonstrated that the balance of the water component over a region can be expressed by:

$$\frac{\partial Wp}{\partial t} + \operatorname{div} \vec{Q} = \overline{E} - \overline{R} \quad \ldots\ldots (7)$$

where $\frac{\partial Wp}{\partial t}$ is the time variation of the precipitable water;

$\operatorname{div} \vec{Q}$ is the water vapor transport vector divergence;

$\overline{E}$ — mean evapotranspiration;

$\overline{R}$ — mean precipitation.

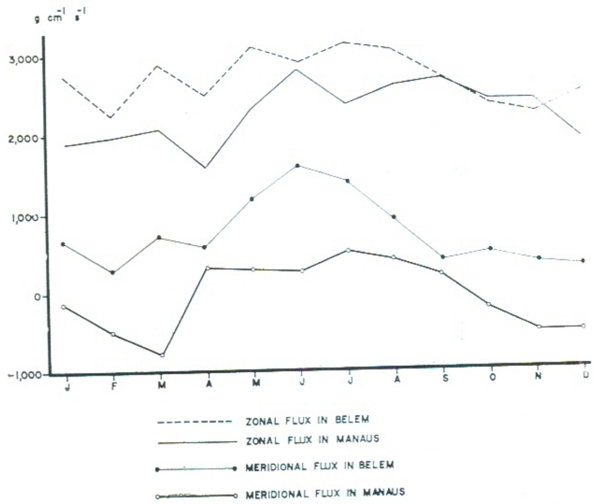

Fig. 5 — Zonal and meridional fluxes obtained in 1972 for Belem and Manaus.

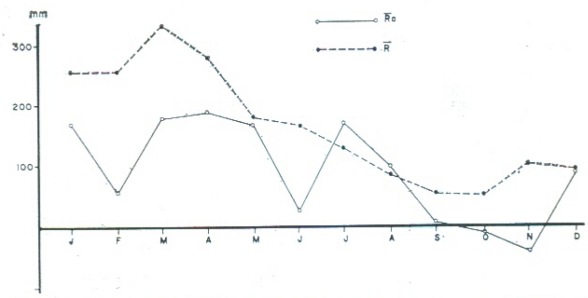

Fig. 6 — Monthly variation of advectvie rain $\overline{Ra}$ and of rain $\overline{R}$ for 1972, measured in the area under study.

In this, as can be seen from the data in Table I and fig. 4,

$\frac{\partial Wp}{\partial t}$ can be considered negligible in relation to the other terms of equation (7). The div $\vec{Q}$ was estimated considering only the value for the zonal water flux between Belem and Manaus, which corresponds to the "advective rain" ($\bar{R}a$), equation 6. Thus equation (7) can be written.

$$\bar{R} = \bar{R}a + \bar{E} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

or

$$1 = \frac{\bar{R}a}{\bar{R}} + \frac{\bar{E}}{\bar{R}} \quad \ldots\ldots\ldots\ldots\ldots \quad (9)$$

where

$\frac{\bar{R}a}{\bar{R}} = k_a$ indicates the fraction of the precipitation from the zonal flux divergence;

$\frac{\bar{E}}{\bar{R}} = k_e$ indicates the fraction of the precipitation from the evapotranspiration within the area under study.

From the analysis of the data in Table I, columns $\bar{R}a$ and $\bar{R}$, one can see that it is necessary to postulate an internal recycling of water vapor within the sector being considered, as in almost all months $\bar{R} > \bar{R}a$, with the exception of July and August. In these months the South Atlantic High Pressure System extends over the continent; there is a reduction of precipitation rates and a consequent relatively more pronounced meridional water vapor transport (Fig. 5).

The application of equation (7) to monthly data has not been successful in 50% of the cases. This deviation was probably due to approximations in the calculations, especially the impossibility of estimating the meridional flux divergence which, although relatively negligible in some months, can become important in the others. This problem, i.e., balance at a monthly level, will only be resolved when aerological information for the region be available for a greater number of years, as well as from more radiosonde stations.

However, when equation (7) was applied on an annual basis, it yielded more consistent data, as :

1. it was applied to a hydrologic cycle;

2. the data for Manaus made it evident that the meridional flux $Q\phi$ is positive from April to September, and negative in the remaining months (fig. 5). Due to this compensation, $Q\phi$ was practically null in the cycle. It is believed that this situation, observed at Manaus, will be applicable to the inner 2/3 of the region under study.

Thus, by applying equation 7 on an annual basis, it was estimated that the advective coefficient k_a is equal to 0,25, giving as a result $k_e = 0.48$, i.e., 48% of precipitation being derived from evapotranspiration, wich is in accordance to estimates given by Molion (1975). This implies an average real evapotranspiration for the region close to 1,000mm. The estimate by means of Thornthwaite's method (Table I) indicates the annual value of 1,600mm. The estimate by means of the Penman formula, using average data (Table I), Villa Nova (1976), indicates an annual value of 1,460mm for potential evapotranspiration. Since in both cases the potential evapotranspiration was considered, it would be expected that, even in the Amazon forest, plant transpiration is smaller than the maximum estimated by the above methods. Thus, our estimate of 1,000mm year^{-1} by the aerological method for 1972 seems to be reasonable.

The calculations indicate that at least in 2 months (October and November) this region functions as a source, supplying water vapor to the region lying west of Manaus (Table I).

TABLE I — Summary of monthly results obtained for 1972. $Q\lambda_i$ is the zonal water vapor flux in Belem; $Q\lambda_o$ is the zonal water vapor flux in Manaus; $\Delta Q\lambda = Q\lambda_i - Q\lambda_o$; $\overline{Ra}$ is the mean advective rain; $\overline{R}$ is the mean rain; E_1 is the mean potential evapotranspiration (Thornthwaite method); $\overline{E}_2$ is the mean potential evapotranspiration estimated by PENMAN's method (Villa Nova et al. 1976); $\overline{W}p$ is the mean precipitable water.

Months	Belém $Q\lambda_i$ gv/cm.s	Manaus $Q\lambda_o$ gv/cm.s	$\Delta Q\lambda$ gv/cm.s	$\overline{Ra}$ mm	$\overline{Wa}$ mm	$\overline{E}_1$ mm	$\overline{E}_2$ mm	$\overline{R}$ mm
Jan.	2640	1857	783	165	39	123	121	255
Feb.	2230	1971	259	51	42	112	117	256
Mar.	2893	2053	840	177	41	115	120	333
Apr.	2489	1587	902	184	43	111	108	281
May.	3075	2296	779	164	41	124	108	180
June	2907	2805	102	21	39	128	110	167
July	3163	2364	799	168	39	143	111	128
Aug.	3031	(2600)	(431)	(103)	(40)	155	130	88
Sep.	2722	2698	24	5	35	153	135	54
Oct.	2380	2404	−24	−6	36	153	142	50
Nov.	2255	2411	−156	−36	40	149	128	98
Dec.	2289	1882	407	86	42	136	124	190

CONCLUSION

As a contribution to the solution of problems in the hydrology, climatology and ecology of the Amazon region, the most significant conclusions of this paper are:

— the Atlantic Ocean water vapor contributed 52% to the regional precipitation, the water vapor coming from the northeastern coast of South America;

— the water vapor was predominantly supplied to the region under consideration by the zonal flux in the east-west direction, 80% of the total vapor being supplied by the 1,000/700mb sublayer flux;

— the values for the water vapor flux at Belem, compared month-to month with those for Manaus, showed higher values for Manaus were 1 and 7% higher, October and November, when the values (1 to 57%), except for the months of respectively;

— the meridional water vapor flux at Belem was predomonantly in the south to north direction, and the 1,000/700mb sub-layer flux contributed 68% to total meridional vapor flux;

— the meridional water vapor flux at Manaus showed a semi-annual alternation in its direction, being from south to north in the period April-September, and from north to south in the other months, being the annual value practically negligible;

— the high values obtained for the precipitable water were a necessary condition, though not sufficient, for high precipitation values. The synoptical and climatological characteristics that give origin to the vertical movements in the region must also be considered;

— the values for precipitable water at Manaus, when compared month-to-month with those for Belem, showed values that were always higher (5 to 35%), the differences found in the period April-September being smaller. The monthly mean value for precipitable water at Manaus was 43mm and in Belem 38mm. This suggest that the region acts as a permanent water vapor source;

— at both locations the 1,000/850mb sublayers contributed ca. 50% of the total precipitable water; up to 700mb the total contribution was 80% and above 500mb the contribution was negligible;

— the monthly mean specific humidity $(\overline{q})$, calculated for the 1,000/500mb layer, was around 9 g kg^{-1}, the values at Belem being a little lower; for the levels above 500mb, the monthly mean specific humidity value was lower than 2g kg^{-1} for both locations;

— a significant role is played by local evapotranspiration in the generation of rain in the area; there were signs of the phenomenon of water vapor recycling nearly throughout the year. Evapotranspiration contributed to 48% of the rains in the region studied.

ACKNOWLEDGMENTS

The authors would like to extend their thanks to the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for the financial support, which made this research possible. To Drs. Peter B. Vose (Project Manager UNDP/IAEA Project BRA/71/556 at CENA and Luiz B. Molion (CNPq/INPE) for the revision of the manuscript and the useful suggestions. To the Climatology and Galeão Area Forecast Center Staff (Brazilian Air Force), for their cooperation and for permitting the access to meteorological information, without which this work could not have been carried out. To the National Department of Meteorology, Rio de Janeiro, Brazil, for the supply of meteorological data.

Resumo

O fluxo de vapor e a água precipitável foram computados sobre a floresta natural Amazônica na faixa entre Belém e Manaus para o ano de 1972. O conceito de ramo aéreo do ciclo hidrológico foi aplicado e as mais significativas conclusões, em base anual foram: o vapor dágua oriundo do Oceano Atlântico contribui com 52% para a precipitação na região e é significante o papel desempenhado pela evapotranspiração local para a precipitação na área; existem indícios do fenômeno da reciclagem do vapor dágua durante o ano. A evapotranspiração contribui com 48% para a precipitação na área estudada. A evapotranspiração real estimada por este método foi de 1000mm ano^{-1}.

BIBLIOGRAFIA CITADA

AZEVEDO, D.C.
1974 — **Chuvas do Brasil: regime, variabilidade e probabilidade de alturas mensais e anuais.** Thesis M.S., UFRJ.

BARNES JR., A.A.
1964 — Atmospheric water vapor divergence: measurements and applications. In: **Humidity and moisture**, vol. II, 513-522. Reinhold Publ. Co., N.Y.

BENTON, G.S.; BLACKBURN, R.T. & SNEAD, V.O.
1950 — The role of the atmosphere in the hydrological cycle. **Trans. Am. Geoph. Union**, 31:61-73.

HARRISON, L.P.
1970 — Calculation of precipitable water. **ESSA Technical Memorandum WBTM TDL 33, US Dept.** Commerce, Weather Bureau, S. Spring, MD, 61 pg.

HOLZMAN, B.
1937 — Use of aerological soundings in determining the sources of moisture for precipitation. **Trans. Am. Geoph. Union**, 18:489-490.

McDONALD, J.E.
1962 — The evaporation precipitation fallacy. **Weather**, London, 17(5) : 168-177.

MOLION, L.C.B.
1975 — **A climatonomic study of the energy and moisture fluxes of the Amazonas Basin with considerations of deforestations effects.** PhD Thesis, Univ. Wisconsin, Madison.

NEWELL, R. E.; KIDSON, J. W.; VICENT, D. G. & BOER, G. J.
1972 — **The General Circulation of the Tropical Atmosphere and Interactions with Extra-Tropical Latitudes.** Vol. I, MIT Press. Mass, USA.

PALMÉN, E. & SODERMAN, D.
1967 — The computation of the atmospheric moisture transport for hydrological purposes. **WMO Reports**, Rept. in WMO/IHD, Genéve, 63 p.

PEIXOTO, J.P.
1968 — O ramo aéreo do ciclo hidrológico. **Fomento**, Lisboa, 6(2) : 11-119.

THORNTHWAITE, C.W. & MATTER, J.R.
1955 — The water balance. **Publications in Climatology**, 8(1). Drexel Inst. of Technology, Centerton. 104 p.

VILLA NOVA, N.A.; SALATI, E. & MATSUI, E.
1976 — Estimativa da evapotranspiração na Bacia Amazônica. **Acta Amazônica**, Manaus, 6(2) : 215-228.

WUNDT, W.
1938 — "Das Bild des Wasserkreislaufs aufs Grund Fruherer und Neurerer Forschungen". **Mitt. Rerchsverb. Dtsch. Wasserwirtschft**, Nr. 44.