

Recycling of Water in the Amazon Basin: An Isotopic Study

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The oxygen-18 content of precipitation in the Amazon basin is characterized by a very small inland gradient, $0.75 \times 10^{-3} \text{‰ km}^{-1}$. This is a consequence of the large contribution of reevaporated moisture to the basin's water balance. A distinct seasonal and regional pattern of stable isotope composition has been recognized and shows the basin to be inhomogeneous from the hydrometeorological point of view. The occasional appearance of very low δ values is believed to be related to the position of the ITCZ rather than to interbasin processes.

INTRODUCTION

The Amazon basin, with an area of 6,000,000 km² approximately, is the world's largest drainage basin. Its outflow is estimated to be $5.5 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}$ [Oltman, 1963, 1967] and constitutes about 15% of the total freshwater flow on the globe. The natural hydrological and ecological balance of the basin which supports the greatest reservoir of vegetation, has not as yet been disturbed (by man) to a significant degree.

Preliminary calculations on the water balance in the central basin by Molion [1975] and Villa Nova et al. [1976] indicated more than half of the precipitated waters to be returned to the atmosphere through evapotranspiration, while about 45% are drained by the river. Mean precipitation is estimated to be 2000–2400 mm yr⁻¹.

Marques et al. [1977] has estimated that in 1972 the inflowing moisture from the Atlantic Ocean accounted for only 52% of the precipitation in the region between Belem and Manaus, while the remaining rain originated from water vapor recycled within the area. Clearly, an important part of the precipitation is engendered in the basin itself. The basin acts not only as a source of its own moisture but also triggers the rain producing process dynamically.

The geomorphological structure of the basin is that of a vast plain with an altitude difference of only 120 m over a range of 3400 km. The basin is bordered in the north by the Planalto das Guianas (~1000 m altitude), by the Planalto Brasileiro in the south which rises to an elevation of 700 m and to the west by the Cordilheira dos Andes (~5000 m). The latter forms a semicircle open toward the east and practically blocks any influence from the Pacific Ocean. The Amazon basin communicates more freely only with the Orenoco basin toward the northwest and in the southwest it is open to the Platina basin through the depression of the 'Chaco region.' As a result of this geographic setting much of the inflowing and reevaporated moisture is expected to condense within the basin.

Widespread development projects are being planned for exploiting the natural resources (water and sunshine) of the Amazon region and some of these are already in stages of execution. These activities result in widespread deforestation, affecting the local water balance. Due to the importance of recycled moisture in the region's water balance these activities can be expected to influence the climate and in particular the precipitation over wide areas in the basin. The study of the feedback mechanisms which operate between evaporation and precipitation thus assumes great urgency. Detailed water bal-

ancing cannot now be carried out because hydrologic data are sparse and radiosonde observations, which are available from Belem, Manaus and Vilhena only, are insufficient for quantifying the moisture flux.

The stable isotopic composition of precipitation is an additional tool for studying the water balance. The isotope content in a precipitating air mass evolves as a function of the depletion of atmospheric moisture through rainout; e.g. a Rayleigh type law [Dansgaard, 1964].

$$R = R_0 \exp \left(\int_1^f \epsilon \, d \log f \right) \quad (1)$$

($R = N_i/N$ is the isotopic abundance ratio, N_i is number of the moles of the isotopic and N of the normal species; $f = N/N_0$; $\epsilon = \alpha - 1$, where $\alpha \equiv$ unit isotopic fractionation factor = $(N_i/N)_L : (N_i/N)_V$; subscripts L , V , refer to liquid or vapor phase, respectively, and subscript zero to the initial state when $f = 1$.)

Under the prevailing conditions of almost homogeneous temperatures and absence of mountains, (1) can be approximated by the closed form expression $R = R_0 f^\epsilon$. Deviation from this equation must be attributed to additional water vapour sources, such as reevaporation. The isotope content is thus a direct measure of the atmospheric water balance.

Some data on the isotopic composition of the water sources of the area were available from the precipitation network organized by the IAEA: tritium and stable isotope data from Belem, Manaus, Brasilia, Cuiaba, Cayenne, Porto Velho have been reported by Dansgaard [1964] and in the IAEA publications 'Environmental Isotope data nos. 1–5' [International Atomic Energy Agency, 1969, 1970, 1971, 1973, 1975]. A preliminary survey of river waters from the Amazon system has been made by E. Salati et al. (unpublished report, 1973) and Matsui et al. [1976]. Although the record is incomplete, some dominant features stand out: (1) Data generally follow the meteoric water line $\delta_D = 8\delta^{18}\text{O} + 10\text{‰}$; (2) the inland gradient $d\delta^{18}\text{O}/dx$ is much smaller than in other continental areas, such as Europe where the gradient is $-0.33\text{‰}/100 \text{ km}$ [Sonntag et al., 1976]; (3) very depleted values of $\delta^{18}\text{O}$ in the precipitation were recorded occasionally at Belem and Manaus. Similar low values, as low as $\delta^{18}\text{O} = -11\text{‰}$, have never been reported at other low latitude coastal sites in the world; (4) relatively high (enriched) δ values are encountered in the northern part of the continent, north of the Amazon basin.

As there is no appreciable temperature variation over large parts of the basin throughout the year, it is, of course, meaningless to discuss the data in terms of the δ -temperature correlation, which in other regions usually dominates the stable isotope distribution. Variability of isotope composition must thus be related to other climatic or synoptic factors.

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DATA COLLECTION

Precipitation and river water was collected at monthly intervals from 1972 at representative sites throughout the basin. The precipitation sampling was performed using the standard procedures of the IAEA network, and yield a composite monthly sample. Location of the sampling stations are shown in Figure 1.

Analyses for the oxygen-18 and deuterium in these samples were performed at the laboratories of CENA. Methods of analysis were the standard ones, and the mass-spectrometric determinations were made on a MAT-230 ($^{18}\text{O}/^{16}\text{O}$) and a GD-150 (D/H) mass spectrometer from Varian Mat.

The complete collection of data is available at CENA. Figure 2 shows the annual march of values for a number of stations which are representative of different geographic and climate zones of the area.

Figure 3 gives the (amount weighted) biannually averaged values of the isotopic composition of precipitation throughout the basin as a function of longitude: since easterlies are the dominant prevailing winds the longitude corresponds to the effective distance from the coast. The mean $\delta^{18}\text{O}$ gradient of 0.75‰/1000 km is very small indeed and about 1/4 of normal

continental gradients. Stations in the northern part of the basin show more positive values, but there is no correlation between isotope data and the climate zones (Figure 1).

Seasonally averaged data for the different stations are shown in Figure 4 as a function of location (monthly data show too much scatter and obscure the overall pattern). A clear seasonal pattern emerges: during the first calendar months there is a noteworthy south to north variation, although the 'inland gradient' is not clearly defined. During April–June the basin is dominated by very depleted isotope values and the inland effect appears as the most important factor, applying equally to the northern, central, or southern portion of the basin. Its magnitude, 2.5‰ in $\delta^{18}\text{O}$ over 20° longitude, is 3 times larger than the annual average. The data of the months July–September are characterized by relatively high δ values, ranging from $\delta^{18}\text{O} = 0$ to -5‰, without any inland gradient. A weak north-south pattern appears and seems to be the reverse of that shown in spring, namely stations in the south of the basin show the more depleted isotopic values. Finally, the last 3 months of the year show an intermediate type of behavior, with a moderate inland $\delta^{18}\text{O}$ gradient of about 1‰/1000 km; isotopic values still tend to be heavy and there is no clearcut pattern in the latitudinal distribution.

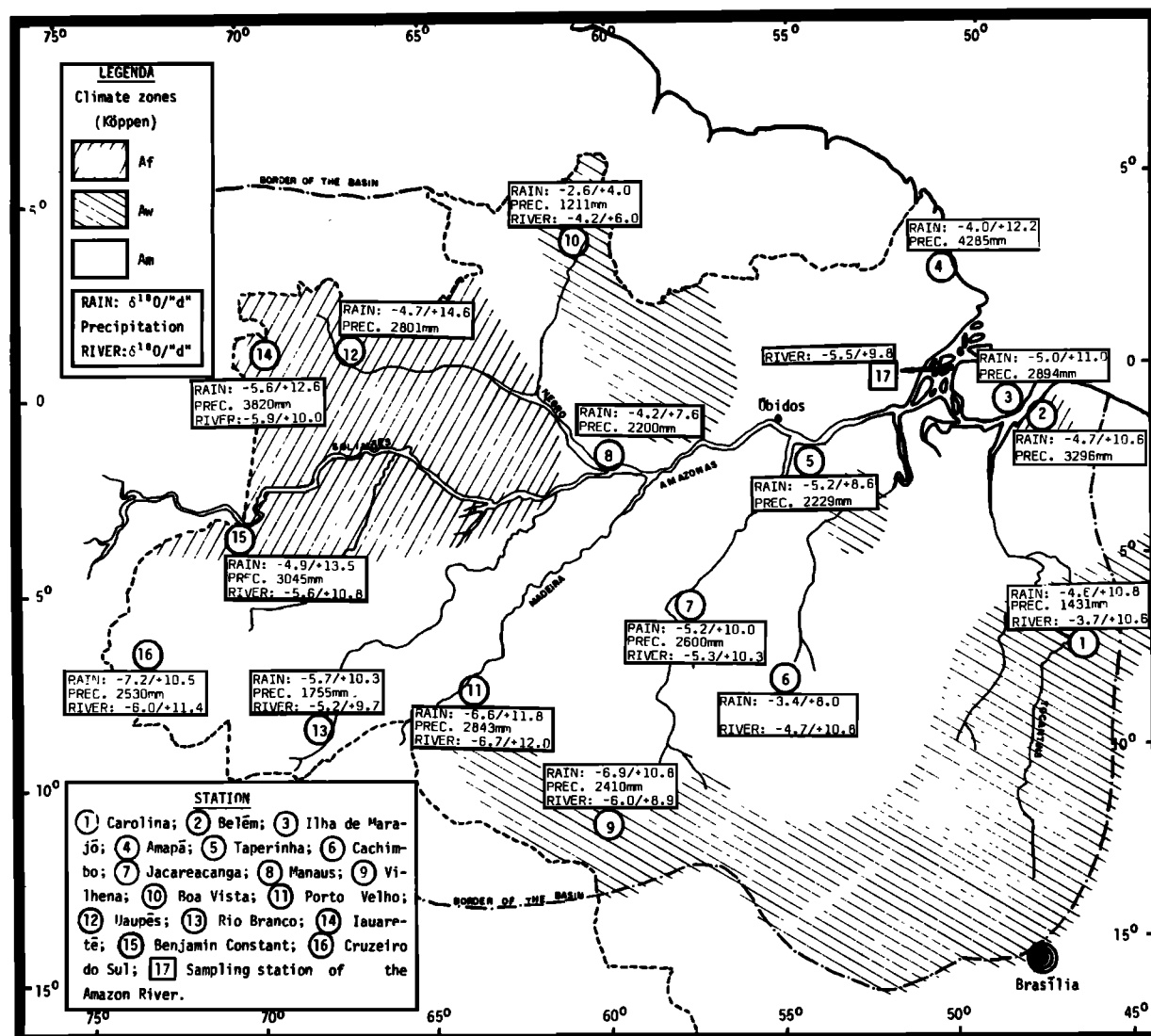


Fig. 1. Location map of rain and river water sampling stations. The mean (weighted) $\delta^{18}\text{O}$ and d excess in precipitation and river water for period October 1972 to October 1973, and annual precipitation amounts are given for each station.

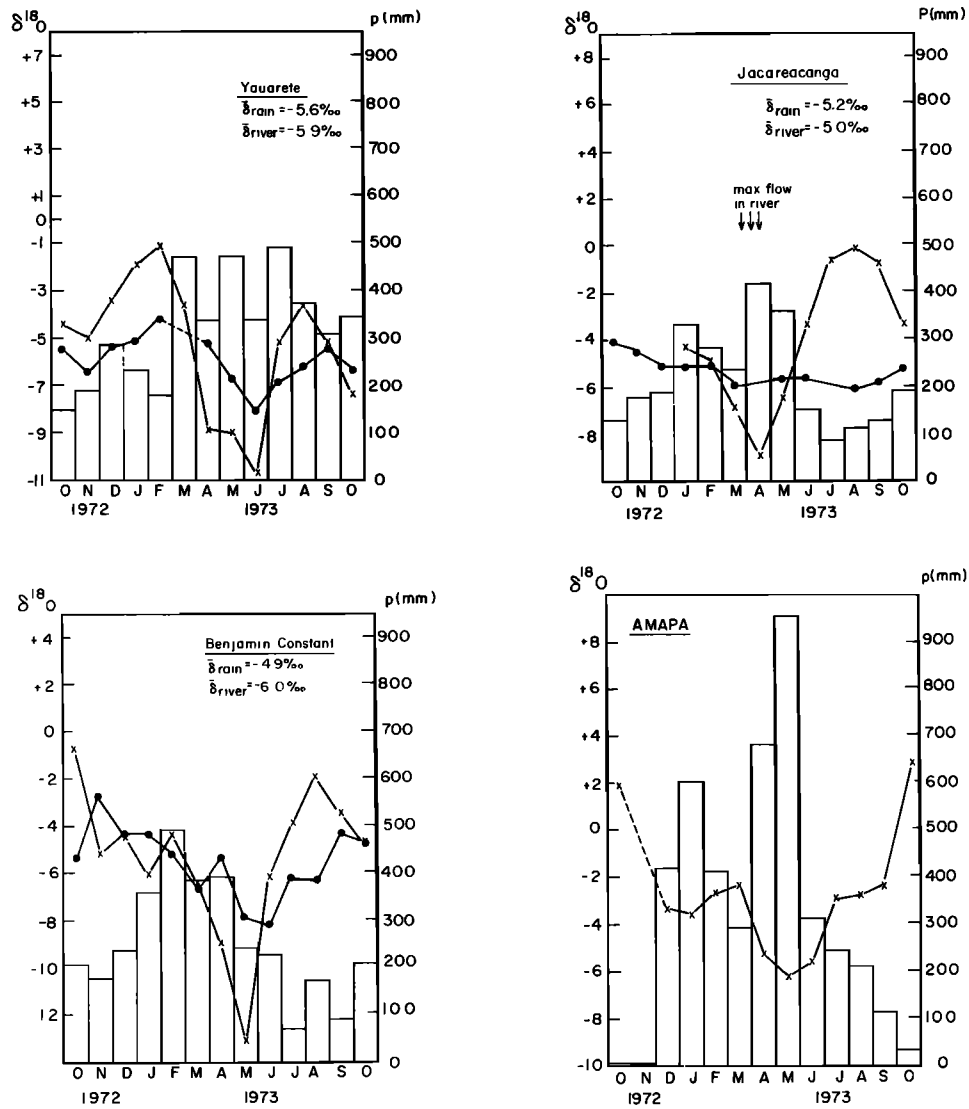


Fig. 2. Annual march of precipitation amounts (histogram and right-hand scale); $\delta^{18}O$ (‰) in precipitation (crosses) and river water (dots) at four representative stations. The mean yearly values are also given.

Precipitation amounts likewise show a yearly cycle, especially in the eastern part of the basin [Trewartha, 1961]. There are some phase differences in the annual cycle at different stations, but on the whole the minimum in the rain curve occurs late in winter (August to October) except for the northern part of the basin, where the drought period is out of phase with the rest of the area and extends from December to April. There is a partial overlap of the period of strongest rains and the period during which precipitation is depleted in the heavy isotopic species. This leads to some correlation between these sets of data especially at Taperinha, on the island of Marajo and at Belem. However, when all data are considered, this correlation is obscured. We therefore conclude that the two effects are not directly related, and that the correlations found are probably fortuitous.

The river data are shown in comparison with the precipitation data for selected points in Figure 1. As expected, there is much less variability in the composition of river water compared to local rain; the river water sample represents an integrated rain sample of the upstream region which extends over longer periods depending upon the holdup in the catch-

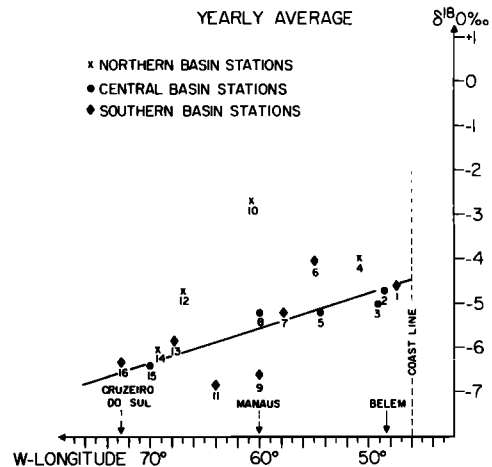


Fig. 3. Biannually averaged oxygen isotope content of precipitation at different stations. Numbers refer to legend in Figure 1.

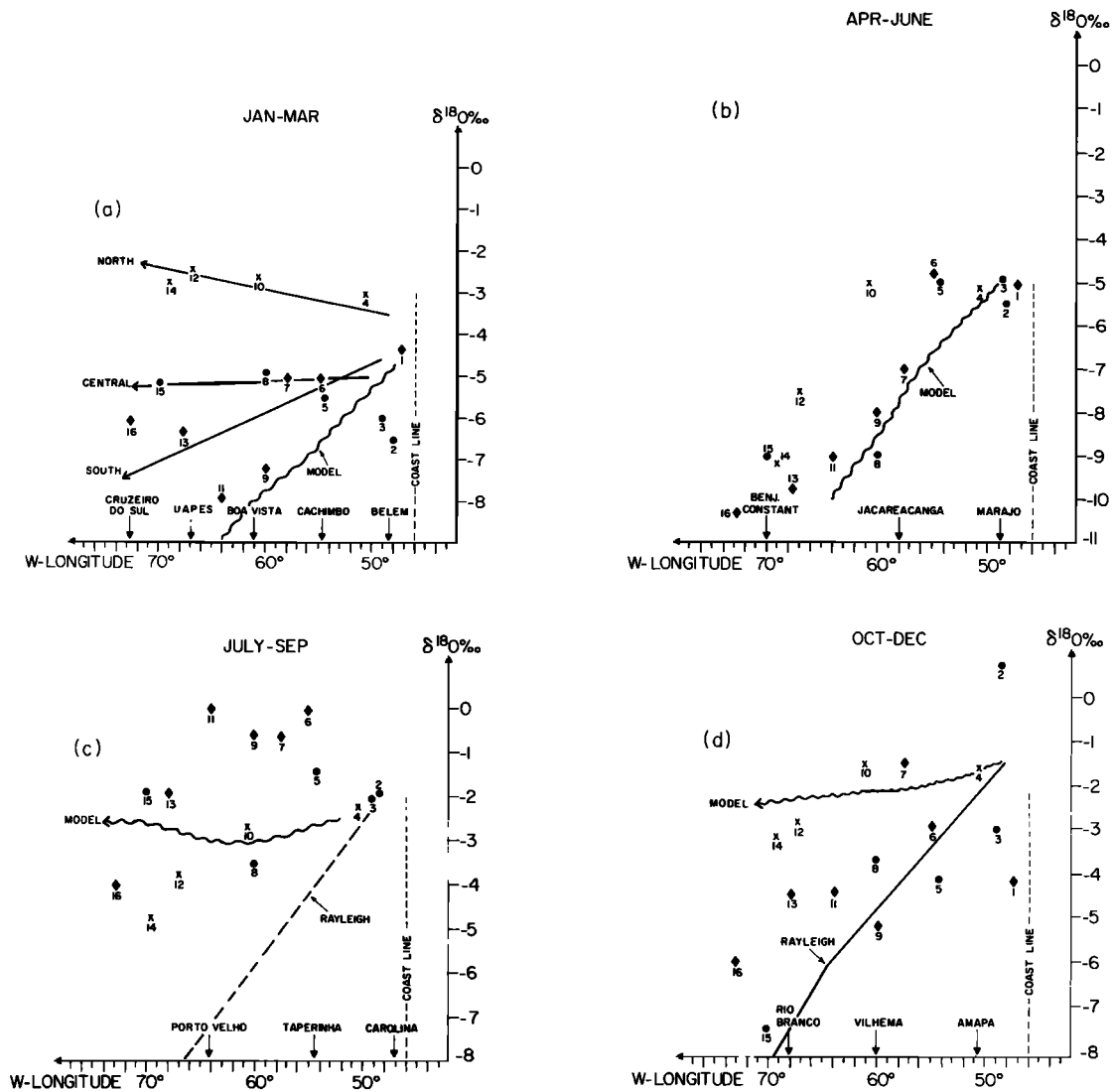


Fig. 4. (a-d) Seasonally averaged oxygen-18 content of precipitation at network stations in Amazon basin. Numbers again refer to legend of Figure 1. The expected evolution of the $\delta^{18}\text{O}$ with distance from the coast according to Dall'Olio's model (which takes the reevaporated moisture into account) and according to a simply Rayleigh model is also shown.

ment area. Annually averaged data are shown on the map (Figure 1), in addition to the amount weighted mean $\delta^{18}\text{O}$ of river and rain at these stations and the value of the deuterium excess parameter d . The 'd excess' parameter as defined by Dansgaard [1964], $d \equiv \delta_D - 8\delta^{18}\text{O}$, places the data point on its appropriate meteoric water (slope 8) line.

The features to be noted are the rather close agreement, at most places, between the rain and river data which may just be a reflection of the very small inland gradients in isotopic composition. However, along the main river system of the Solimões and Amazonas there is a marked, though small, difference in isotopic composition. River waters at Benjamin Constant, Manaus and near the river mouth are depleted in heavy isotopes (by about -1‰ for oxygen-18) relative to local rain. The most interesting aspect of these data, however, is the pronounced, lower value of the d excess parameter in the river water compared to rain, in some cases lower by as much as 3‰ .

The discharge of the Amazon river system was sampled near its mouth in the 'Canal sul' north of the Island of Marajo [Reis

et al., 1977]. The total river discharge at this point cannot be directly measured, but by weighting the isotope data by the flow rate of the Amazon as measured at Obidos (the least narrows on the river before the coast) one finds a value of $\delta^{18}\text{O} = -5.55\text{‰}$ and $\delta_D = -34.6\text{‰}$ for the mean annual isotopic composition of the discharge of the Amazonas. It is noteworthy that this value lies on the meteoric water line of $\delta_D = 8\delta^{18}\text{O} + 10\text{‰}$.

MODELING OF THE ISOTOPE BALANCE IN THE CENTRAL BASIN

Dall'Olio [1976] has attempted a simple isotope balance for the central part of the basin, based on the observed predominant zonal flow [Newell, 1971]. A minor latitudinal component is neglected. This model considers a 5° wide strip from the equator southward, and extending westwards to the Peruvian border. The vapor influx from the Atlantic Ocean is estimated from the wind and humidity measurements by radiosonde at Belem. The isotopic composition of this flux is calculated by taking the mean value for precipitation at the

ocean side stations of Belem, Amapa and three stations on the Marajo Island (São Sebastião, Santa Cruz do Arari and Cachoeira do Arari), and assuming them to be in isotopic equilibrium with the marine vapor. The model strip is then subdivided into 3° wide segments, for each of which an isotopic balance is performed, assuming the depletion of the heavy isotopes due to their preferential removal in rain is described by a Rayleigh equation: $\Delta\delta = f^{\alpha} - 1$, with the appropriate isotopic liquid-vapor fractionation factor for the 850 mb level. The calculations were performed taking the reevaporated moisture in the atmospheric water balance into account in the following manner: the potential evapotranspiration as calculated by *Villa Nova et al.* [1976] was used as the reevaporation term and the isotopic composition of the evaporated vapor is

taken, for each period, as that of the rain in the respective segment.

The computed values (3 month averages) of the isotope content of rain to be expected in these two cases are shown in Figure 4 together with the actually measured isotope data in the basin. In Figures 4c and 4d the Rayleigh plot obtained from (1) (which neglects the reevaporation term) is also shown.

DISCUSSION

The Amazon basin appears, at first sight, to be a rather uniform hydrometeorological unit. However, the complexity of the isotope data with their seasonal and geographic variability, demonstrates the inhomogeneity of the basin from the hydro-

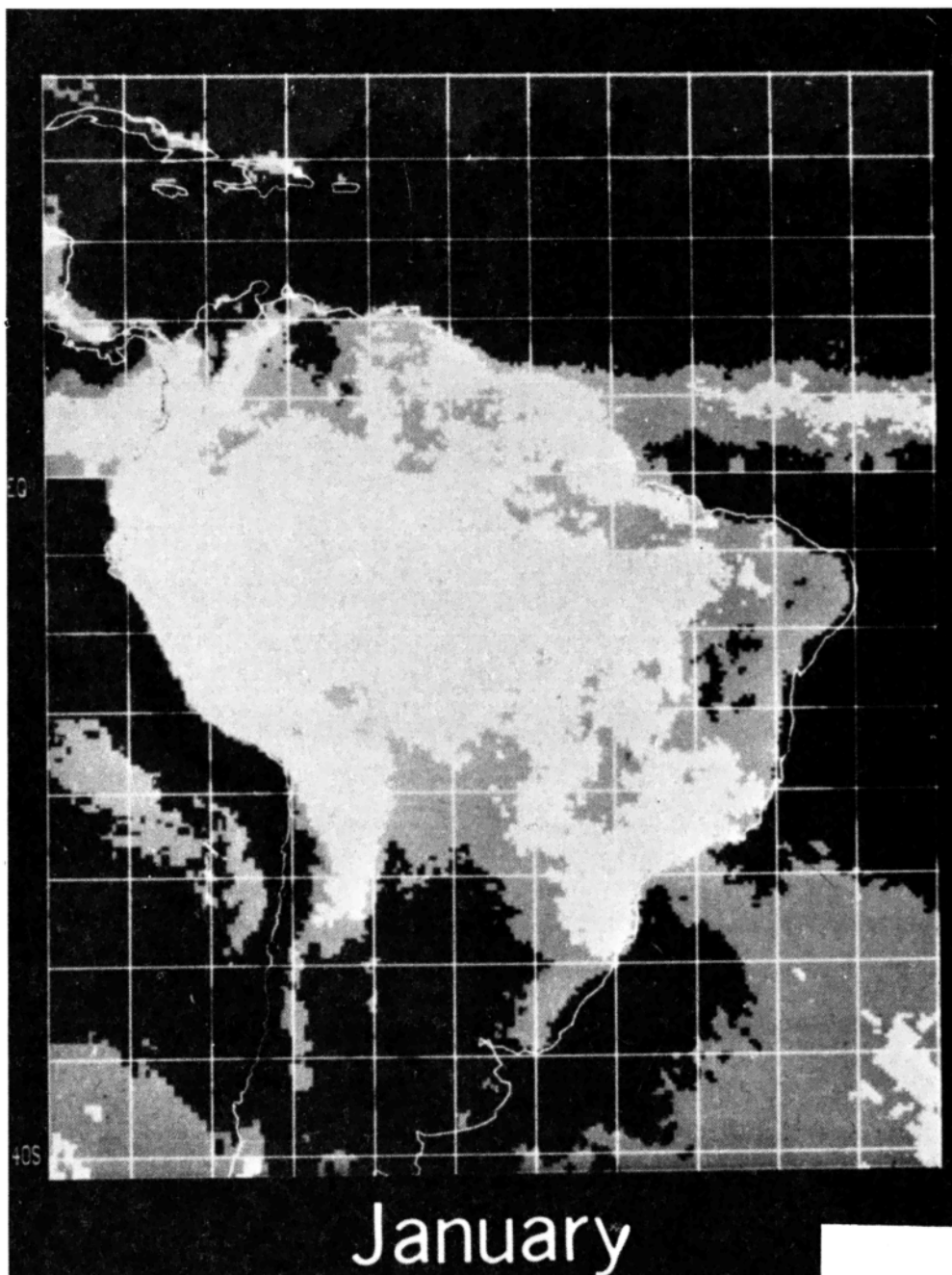


Fig. 5a

Fig. 5. Superimposed 4-year averaged cloud pattern as observed by stationary satellite for months of January, April, July, and October.

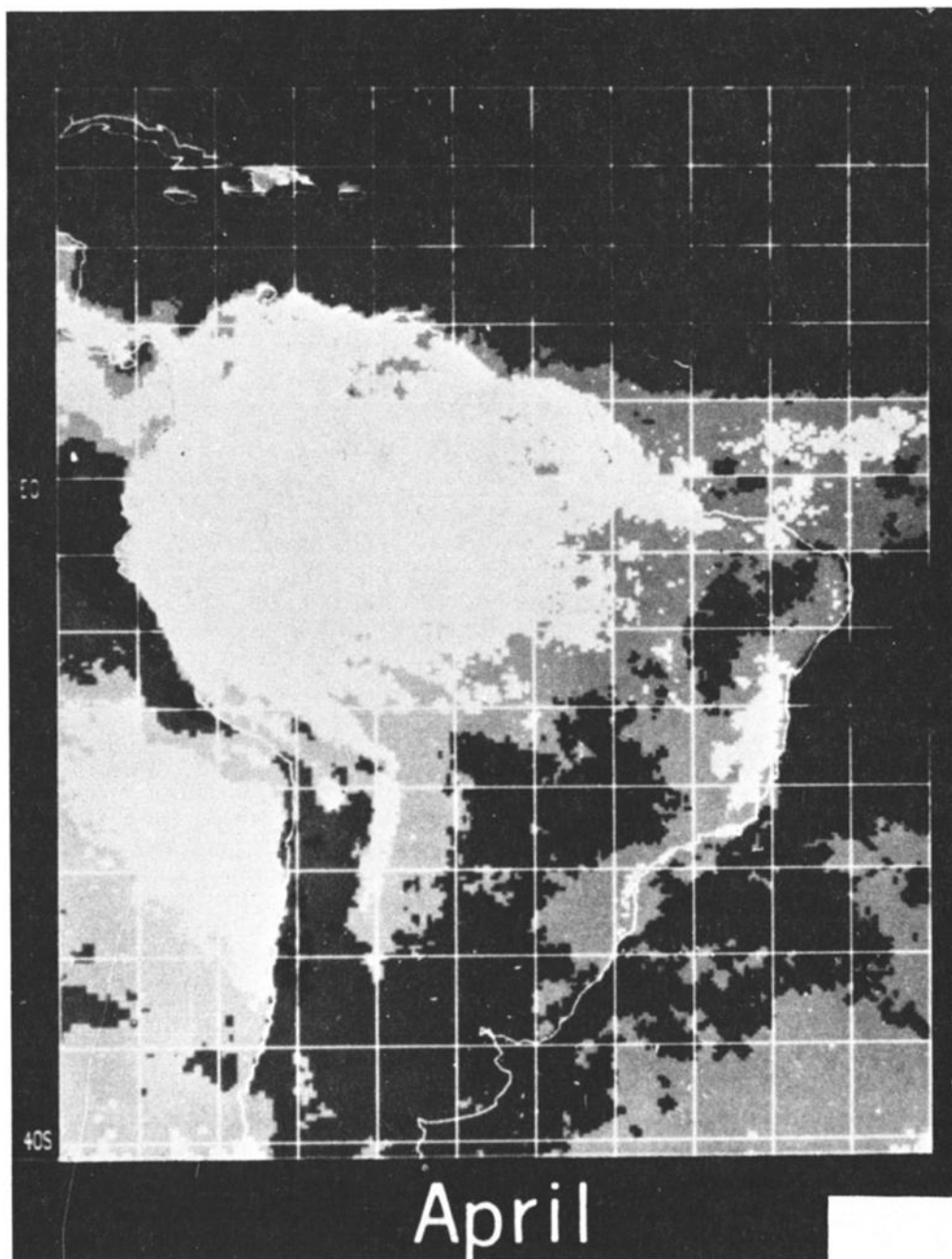


Fig. 5b

meteorological point of view. The small inland gradient of the isotopic composition of the precipitation confirms the importance of the reevaporated moisture in the water balance of the area. Comparison of data with results of the model calculations shows that this effect varies both with the season and with the location.

A comparison between the advected vapor flux, whose isotopic composition is estimated to be $\delta^{18}\text{O} \sim -11.5 \pm 1\text{‰}$, and the river discharge ($\delta^{18}\text{O} = -5.5\text{‰}$) disproves the notion of complete condensation of all inflowing moisture within the basin. Assuming a Rayleigh law to describe the isotopic depletion during rainout, one finds that a net 44% (i.e., taking the reevaporated moisture into account) of the advected moisture leaves the basin in vapor form with a mean isotopic composition of $\delta^{18}\text{O} = -19.3\text{‰}$, i.e., depleted by about 7.8‰ ($\delta^{18}\text{O}$)

relative to the advected marine moisture. This fraction however, changes during the year as a result of the variation of the water yield of the basin. The isothermal character of the climate results in fairly constant values of the (potential) evapotranspiration rate in the basin; *Dall'Olio* [1976] has estimated an increase of only 20% during the drier season of August–November compared to the rest of the year. Precipitation in the basin, on the other hand, changes by at least a factor of 2 between summer and winter. According to the estimates of *Dall'Olio*, the unexploited (net) moisture fraction varies from 15 to 20% during the rainy period, to close to 100% in October and November, when evapotranspiration more or less compensates for the water loss by rainout.

Such model calculations can serve, however, only as rough guides, since both the advected moisture and the evapotranspi-

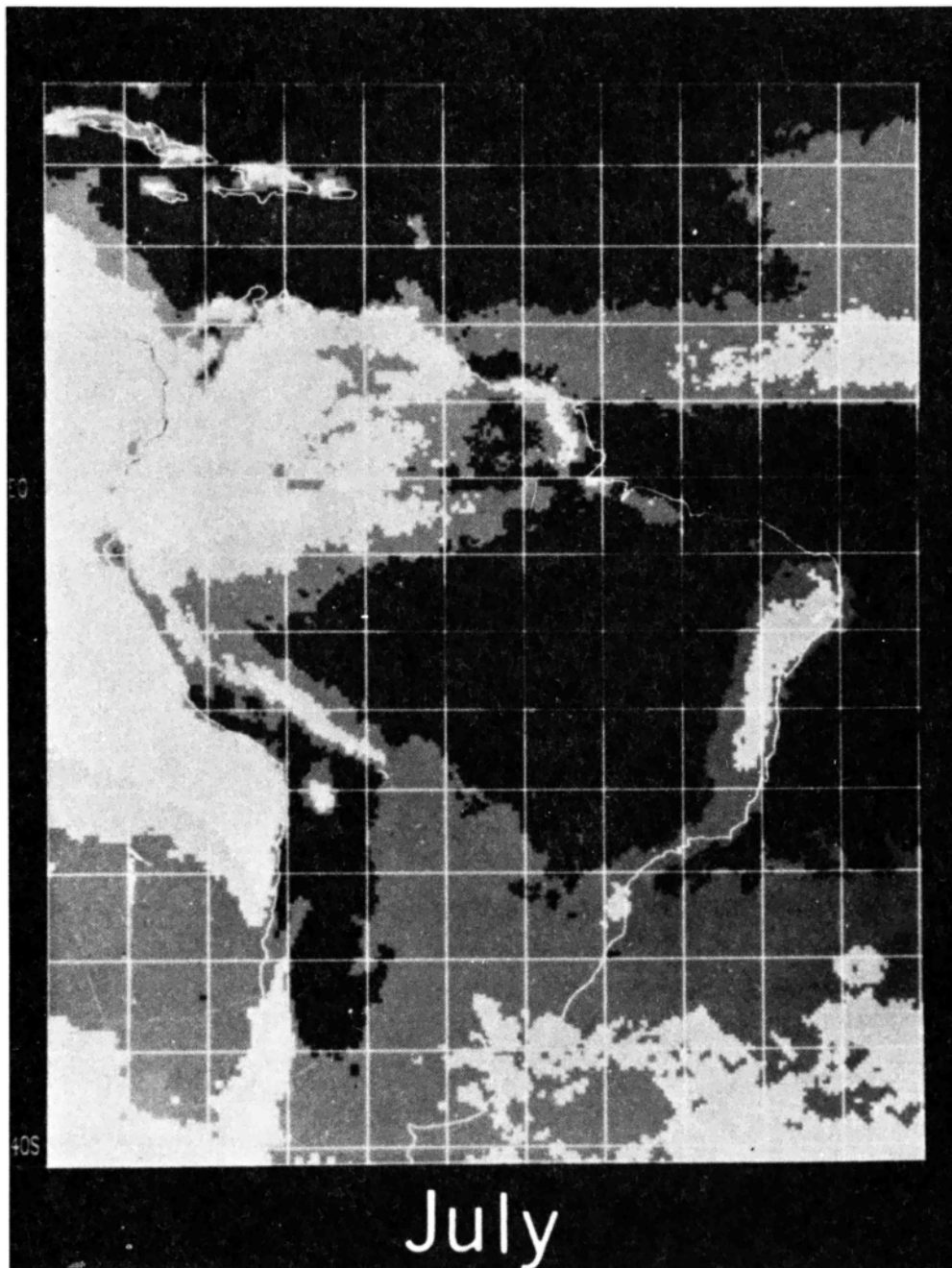


Fig. 5c

ration term are only estimates. For example, *Molion* [1975] found differences of 50% or more in the estimate of the potential evapotranspiration by different methods of calculation. The isotopic data then become very useful tools for testing any suggested water balance pattern.

During the months of July–September, the complete absence of an inland isotope gradient is indeed in agreement with the predictions of the model as shown in Figure 4c. Data from the early summer period (October–December) show a similar pattern. There is, however, a much larger scatter, apparently due to the early onset of the rainy season in some years.

The model calculation overestimates the depletion of the isotopes in precipitation somewhat during the rainy months of April–June, especially in the western part of the basin. Possibly, there are additional sources of advected moisture in the

interior of the basin. Indeed the assumption of negligible latitudinal air exchange breaks down in the western part of the basin, which is an area of convergent flow. During the period of January–March, a marked latitudinal component in the air motion (Figure 4) is reflected in the north to south gradient of the isotopic composition.

The isotope data confirm one result of the model calculation, namely, that the evapotranspiration becomes the dominant factor during the southern hemisphere winter months.

An independent indication of the importance of the re-evaporated moisture in the atmospheric water balance is given by the d excess parameter. As can be seen in Figure 1, where the mean isotope $\delta^{18}\text{O}$ values of rain and river water are plotted for the year October 1972 to September 1973, the precipitation in the central basin consistently has a higher

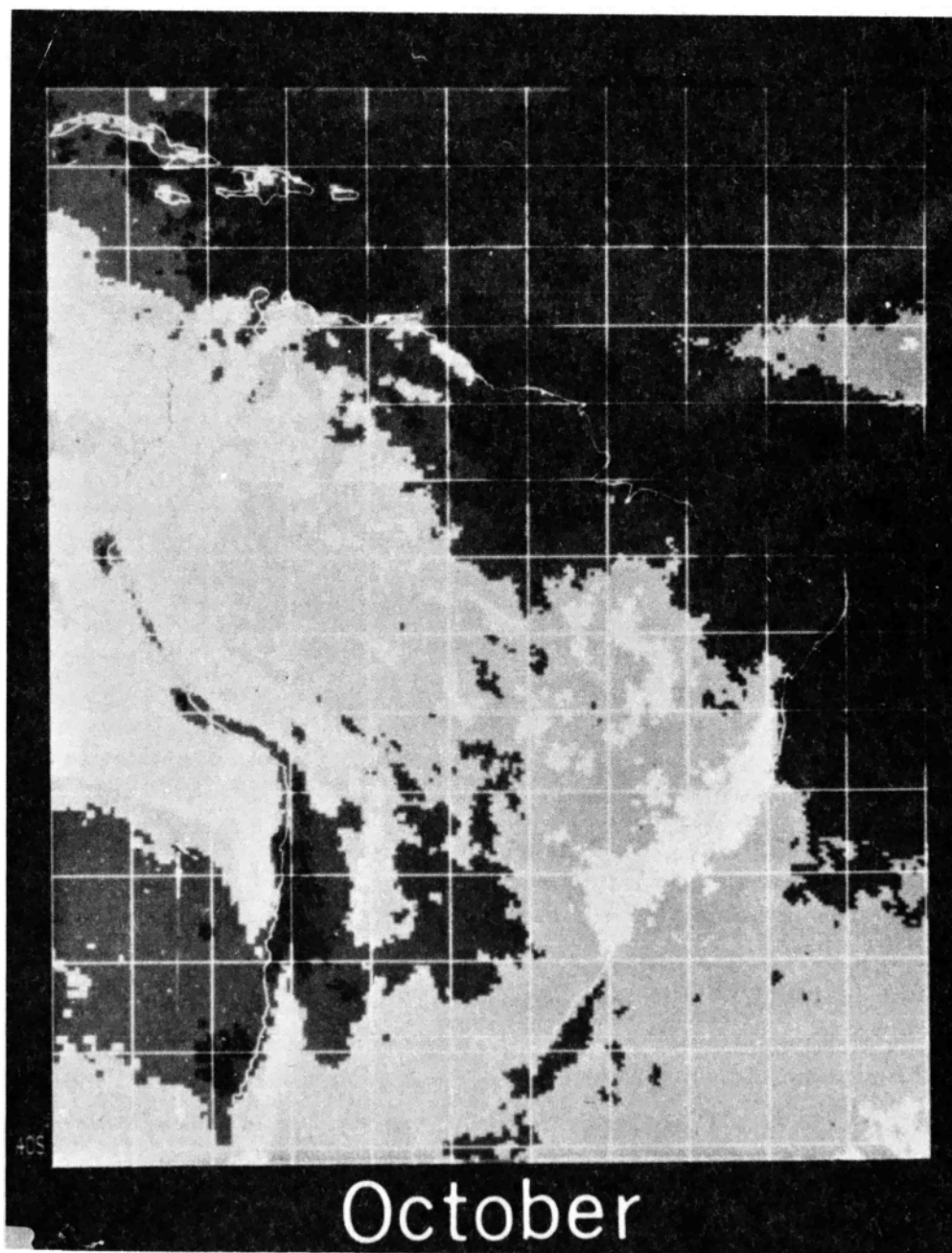


Fig. 5d

value of d than in river water, whereas along the margins of the basin there is much closer agreement between rain and water isotope composition. In a west to east traverse the d excess of the Amazon is slightly reduced, from values of $d = +10.8\text{‰}$ near the Peruvian border, to the final value of $d = +9.8\text{‰}$ at the outflow point.

During free surface evaporation the heavy isotopic species are enriched along evaporation lines of slopes of less than 8, so that the value of the deuterium excess decreases in the residual waters. Conservation of matter then dictates that the evaporated moisture be deuterium excessive; the precipitation resulting from such vapor will then be characterized by values of $d > 10\text{‰}$. The values of d can then be taken as an indicator of recycled water. Although this information cannot be utilized for a quantitative measure of the reevaporation process in the basin, as we do not know the relative contribution of trans-

piration and free surface evaporation to the reevaporation flux (transpiration does not fractionate between the isotopes). One can however pinpoint the areas where large amounts of water are being recycled. These areas evidently are the central and eastern part of the basin, whereas in the western and southern margins the effect is less noticeable, and the role of reevaporated moisture is therefore considered to be less important.

Discordantly low δ values are recorded throughout the basin during April and May and occasionally during the late summer months of December–March. These low δ values are not due to any large inland isotope gradient (even though the measured gradient during this rainy season is larger than during the dry season, Figure 4) but rather there is at times a downward shift of the whole isotope pattern in the basin, including the coastal station in the east. During January 1974, as an example, isotopic compositions which are depleted in the

heavy isotopes were recorded at the coastal areas, but do not seem to penetrate inland at all. We can conclude that the low isotopic values are imposed on the basin from outside.

It has been shown that the period under discussion is a peak rain season in parts of the basin, without however establishing a clearcut correlation between the amounts of rain at any place and time and their isotopic composition. We note, however, that during this period the intertropical convergence zone (ITCZ) moves southwards into the latitude of the Amazonas basin, as is visualized in a striking manner through the satellite pictures of the associated cloud fields (Figure 5). These pictures were kindly put at our disposal by Molion. The coincidence between the position of the ITCZ and the isotopic data is suggestive, implying that the vertical mixing in the convergence zone and resultant cloudiness, affects both the isotopic composition and the rain patterns.

Unfortunately, there are no measurements at sea in the area affected by the ITCZ to test whether the abnormally depleted ^{18}O values are encountered over the ocean as well. However, the 'initial value' of the isotope composition of marine air during these months, computed by assuming liquid-vapor isotopic equilibrium at the coastal stations, yields values which are depleted relative to normal marine air as reported by Craig and Gordon [1965] over the Atlantic Ocean.

The satellite pictures also show the seasonal shift in the wind pattern (as indicated by arrows); the change in the latitudinal component of air motion is clearly mirrored in the isotope data, in particular with regard to the relation between the stations in the northern and southern part of the basin.

Although the time and space variations in the reevaporated moisture emerges quite clearly from the data presented here, there is, of course no solution from these data to the more fundamental question of the dynamics of the rain producing process, and to the effects which changes in the evaporation will have on the buildup of clouds and on the precipitation pattern. As pointed out by Friedman [1977] from observations on Marajo island, the absence of a dense plant cover may have far-reaching effects. It has become clear, however, that these questions will have to be studied in a detailed manner, separately for different parts of the basin and during different seasons.

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