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Mechanisms of Water Recycling in the Amazon Basin: Isotopic Insights

This paper presents an analysis of the isotopic composition of monthly rainwater samples collected at two sampling stations in the Amazon Basin over a period of 20 years. The results of this analysis not only reconfirmed the importance of evapotranspiration in water recycling but also pointed to the important role of direct evaporation from open water bodies and the forest canopy. Preliminary interpretations suggest that during the rainy season evapotranspiration is the primary source of water cycling from the land to the atmosphere, while during the dry season evaporation becomes an important source.

INTRODUCTION

The Amazon Basin encompasses an area of 6.4 million km^2, with an average precipitation of 2200 mm yr^{-1}. These figures represent a flux of $14.1 \cdot 10^{12}$ m^3 yr^{-1} of water into the basin (1). The ultimate discharge of water from the basin is estimated to be near 200 000 m^3 s^{-1}, or $6 \cdot 10^{12}$ m^3 yr^{-1} (2). Therefore, approximately 60% of the yearly precipitation within the basin is returned to the atmosphere (3, 4).

The fluxes of water between land and atmosphere are important facets in the spatially and temporally complex hydrologic cycle of the Amazon Basin; a cycle which significantly influences the various other biogeochemical cycles within the basin (5). The influence of the Amazon hydrologic cycle also extends to global scales, as the condensational energy released by convective precipitation within the basin has been shown to be of sufficient magnitude to impact global climate patterns (6). Therefore, a better understanding of the hydrologic cycle of the Amazon will not only contribute to efforts to understand other biogeochemical cycles within the basin, it will also contribute to efforts to understand global climate patterns. Studies such as this are especially important today, as continued deforestation transforms thousands of square kilometers from forest to pasture (7). The effects of deforestation may significantly modify the current hydrological cycle of the basin (8).

The first studies concerning the meteorology and hydrology of the Amazon measured fundamental climatological parameters like temperature, precipitation, solar radiation, and winds (9–12). With respect to the water balance in the region, studies were conducted on two different scales. Local-scale studies involved measurements made in small basins of a few square kilometers (13–16), while regional-scale studies involved measurements made over thousands of square kilometers (9, 17, 18). Similar results were obtained for both scales, indicating that approximately 50% of Amazon precipitation returned to the atmosphere, while the remainder was fluxed out via runoff. These results strongly suggested the importance of the forest in maintaining the water balance in the basin.

While these studies deal with basins as a whole, whatever working scale, Dall'Olio (19) divided the Amazon Basin into different sectors and analyzed the evolution of the water vapor by studying the behavior of oxygen and deuterium isotopes in each sector. This study also came to the general conclusion reached by previous studies; the present precipitation pattern observed in the basin is a function of the vegetation cover, i.e. the rain forest. The outcome of these isotopic studies was a model, the Dall'Olio-Salati model, which attempted to explain the isotopic behavior of precipitation in different regions of the basin as a function of a mixture of water originated from two main sources, the Atlantic ocean and the rain forest (3, 4, 20).

The original Dall'Olio-Salati model was developed using a limited set of data, consisting of monthly rainwater sampling at about 15 stations during the years 1972-1973. Since that time, we have continued sampling several key stations in the Amazon Basin. The analysis of this extended data base is the main objective of this paper. Our specific tasks are 1) to compare the results of this extended data base with the trends and values predicted in the Dall'Olio-Salati model for samples collected in Belém and Manaus; and 2) to propose possible mechanisms which could explain the discrepancies found between the values predicted by the model and the results observed in the extended data base.

DALL'OLIO-SALATI MODEL

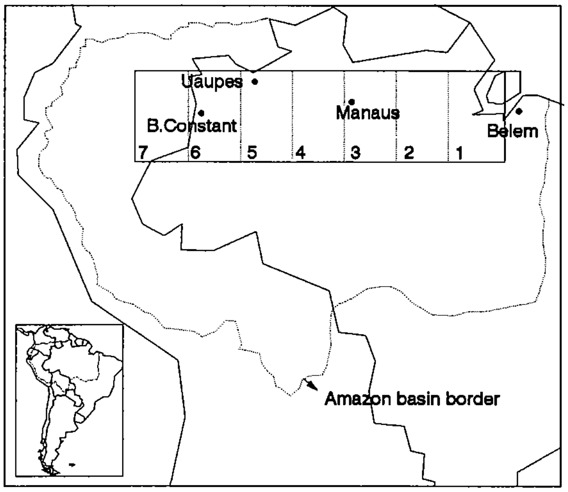
The Dall'Olio-Salati model is based on the assumption that as an air mass moves inland and loses water through precipitation, rainfall will became progressively depleted in heavy isotopes. The pattern of this depletion, assuming steady-state conditions in the atmosphere, can be demonstrated by a Rayleigh type equation. However, the depletion observed in rainwater samples was much smaller than was to be expected based on the amount of precipitation and the Rayleigh law (3, 4, 19, 20). This lack of observed depletion was explained by the recycling of water through the evapotranspiration in the forest (Fig.1). Evapotranspiration, which is a non-fractionating process with respect to isotopes, returns to the atmosphere water of isotopic composition similar to its source (rainwater), which in turn is isotopically heavier than the isotopic composition of the water vapor from which the rain came. Therefore, as the air mass moves inland it will receive a constant input of isotopically heavier water supplied by the rain forest through evapotranspiration. As a result, the depletion in the isotopic composition of the vapor and rainwater would be smaller than the values predicted by the Rayleigh equation.

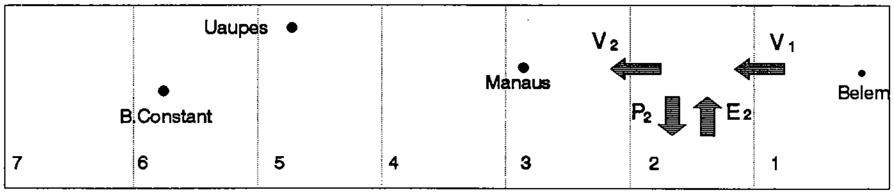
RESULTS

Initially we compare the results predicted by the Dall'Olio-Salati model with the sample data (Fig.2a and 2b). The most striking difference is observed for the rainy season (December-May). For instance, from January to March, while the model predicts values of $\delta^{18}O$ around -11% (SMOW) for Manaus the observed data show values around -5 to -7%. The model predicts isotopically lighter values than the sample data show, even when water introduced by evapotranspiration is considered.

To explain this discrepancy we formulate three hypotheses. 1) The amount of water being evapotranspired by the forest was underestimated by Dall'Olio (19). Evapotranspiration is a source of isotopically heavy water, increasing its amounts would return to the atmosphere a greater amount of isotopically heavy water (20). While this hypothesis maybe valid, for there are very few data for evapotranspiration in that region, the increase would have to be substantial to produce the observed discrepancy. 2) There is an additional and as yet unmeasured water-vapor source for the basin. This hypothesis may be supported by the existence of a significant latitudinal component in the air motion during January to March, which is reflected in the North-South gradient of the isotopic composition of rainwater in the basin. Previous workers have noted that relatively heavy isotopic

Figure 1. Amazon basin and the Dall'Olio-Salati model. A simple mass and isotopic balance was developed for each sector. The output from each sector (V_2) was calculated summing its input (V_1) to the evapotranspiration (E_2) minus the precipitation (P_2).





1) One water source (ocean)

$$\delta P_2 = \delta V_1 + \epsilon$$

$$\delta V_2 = \delta V_1 + \epsilon \times \ln f_1$$

2) Two water sources (ocean and forest)

$$\delta P_2 = \delta V_1 + \epsilon$$

$$\delta V_2 = \left[\frac{(\delta V + 1)(V_1 - P_2) + (\delta E_2 + 1)(E_2)}{(E_2 + V_1)} - 1\right] + \epsilon \times \ln f_1$$

The classical δ notation is defined as follow:

$$\delta(\text{‰}) = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right) \times 1000$$

where:

$R_{\text{sample}} = \frac{^{18}O}{^{16}O}$ or $\frac{D}{H}$ relation of the sample

$R_{\text{standard}} = \frac{^{18}O}{^{16}O}$ or $\frac{D}{H}$ relation of the standard

Standard: VSMOW

where:

δV_1 = isotopic composition of the atmospheric water vapor in sector 1
δV_2 = isotopic composition of the atmopheric water vapor in sector 2
δP_2 = isotopic composition of the rain water in sector 2
δE_2 = isotopic compostion of the evapotranspired water in sector 2
V_1 = water vapor amount transported from sector 1 to sector 2
V_2 = water vapor amount transported from the sector 2 to sector 3
P_2 = precipitation in sector 2
E_2 = water vapor amount from evapotranspiration in sector 2
f_1 = net water content in the airmass of sector 1
ϵ = isotopic fractionation factor

signatures are generally observed in the northern part of the Amazon Basin (3, 4). Therefore, if an additional water vapor source exists, it likely originates in the northern part of the basin. 3) The isotopic composition of the atmospheric water vapor and rain are influenced by the Inter Tropical Convergence Zone (ITCZ) which is very active over the Amazon during this time of the year (3, 4). The ITCZ could affect both the pattern and isotopic composition of precipitation over the Amazon Basin; very light isotopic values are observed at coastal stations where it is active, but the potential for the ITCZ to conversely affect the isotopic composition in the interior of the basin is virtually unknown. It appears that the observed discrepancy may result from some interplay of these factors, but the relative contributions of each remains unknown.

A second discrepancy occurred during the dry season (June-November), where the model predicted larger values of δ ^{18}O for Manaus than were observed. In order for the data to agree, there must be some unconsidered mechanism for reducing the isotopic values or an additional source of depleted water vapor. Note that this discrepancy is opposite of that for the rainy season where an explanation for isotopically enriched water is needed.

First, it can be argued that evapotranspiration was overestimated during the dry season, while during the rainy season evapotranspiration was underestimated. Second, the existence of a external and/or internal isotopically depleted atmospheric water-vapor source may be assumed. Third, in this period of the year the ITCZ is far north from the Amazon Basin and therefore plays no major role.

The first hypothesis can not be directly tested, but it is unlikely that Dall'Olio (19) would underestimate the evapotranspiration rate during the rainy season and overestimate the same process during the dry season. With respect to an external water source during this period of the year, Marques et al. (21) did show that a minor South-North latitudinal component may be possible during the months of August to September. The air mass in this case is continental and should be depleted in isotopes. Although considered as a possible explanation, the low magnitude of the phenomena and the fact that the depleted water source is needed during November-January, not

August-September, reduces the probability of this mechanism being solely responsible for the extra water source.

The second possible water source should then be internal to the basin. As is well known, evaporation from open water bodies produces isotopically lighter water vapor. There are a great number of lakes in the Amazon Basin, especially in the floodplains. During the dry season the volume of water in these lakes is significantly reduced (22), indicating that part of the water volume of these lakes returns to the atmosphere via evaporation. Another possible mechanism is direct water evaporation from the forest canopy. Leopoldo et al. (15) showed that as much as 25% of the precipitation can be trapped on the leaves and return to the atmosphere via evaporation. Obviously, canopy evaporation can produce depleted vapor only if a fraction of the trapped water evaporates. In consideration of these points, it is reasonable to assume that evaporation from lakes and canopy forest may be an important source of isotopically light water to the atmosphere.

In order to track the presence of this evaporated water in the atmosphere during this period of the year we will use the so-called deuterium excess parameter (δ), defined as $\delta = \delta D - 8 \cdot \delta^{18}O$ (23, 24). With the prevailing isothermal condition throughout the basin (1) and the assumption that recycling of water occurs primarily through evapotranspiration, the deuterium excess parameter should be constant and close to the classical value of 10%. On the other hand, if the water recycling primarily occurs through evaporation, the deuterium excess parameter of the water vapor generated should be greater than 10%, causing the data to plot above the meteoric water line (Fig.3a). Consequently, if this vapor is part of the next precipitation event, the rain will also show a deuterium excess parameter greater than 10%.

A marked increase in the deuterium excess parameter is observed in the Amazon region, from about 10% at Belém to about 13% at Manaus. Values of $\delta^{18}O$ versus δD for the rainy season (December-May) are distinct from values for the dry season (June-November) (Fig. 3b and 3c). During the rainy season the data plotted along the meteoric waterline, as indicated by a deuterium excess value equal to 10%. On the other hand for the dry season the data plot above the meteoric waterline, resulting in a deuterium excess parameter of 14%. This trend is further supported by monthly variability of the global radiation at the surface (Fig. 4). During the dry season (June-No-

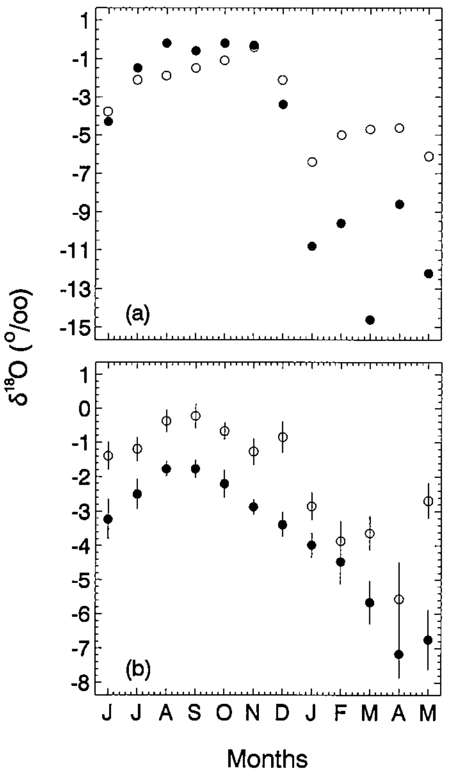


Figure 2. Averaged monthly values of $\delta^{18}O$ rainfall for Belém (o) and Manaus (•). (A) Values as predicted by the Dall'Olio-Salati model considering the contribution of evapotranspiration. (B) Averaged monthly values for samples collected between 1972 to 1986. The standard errors are represented by vertical bars.

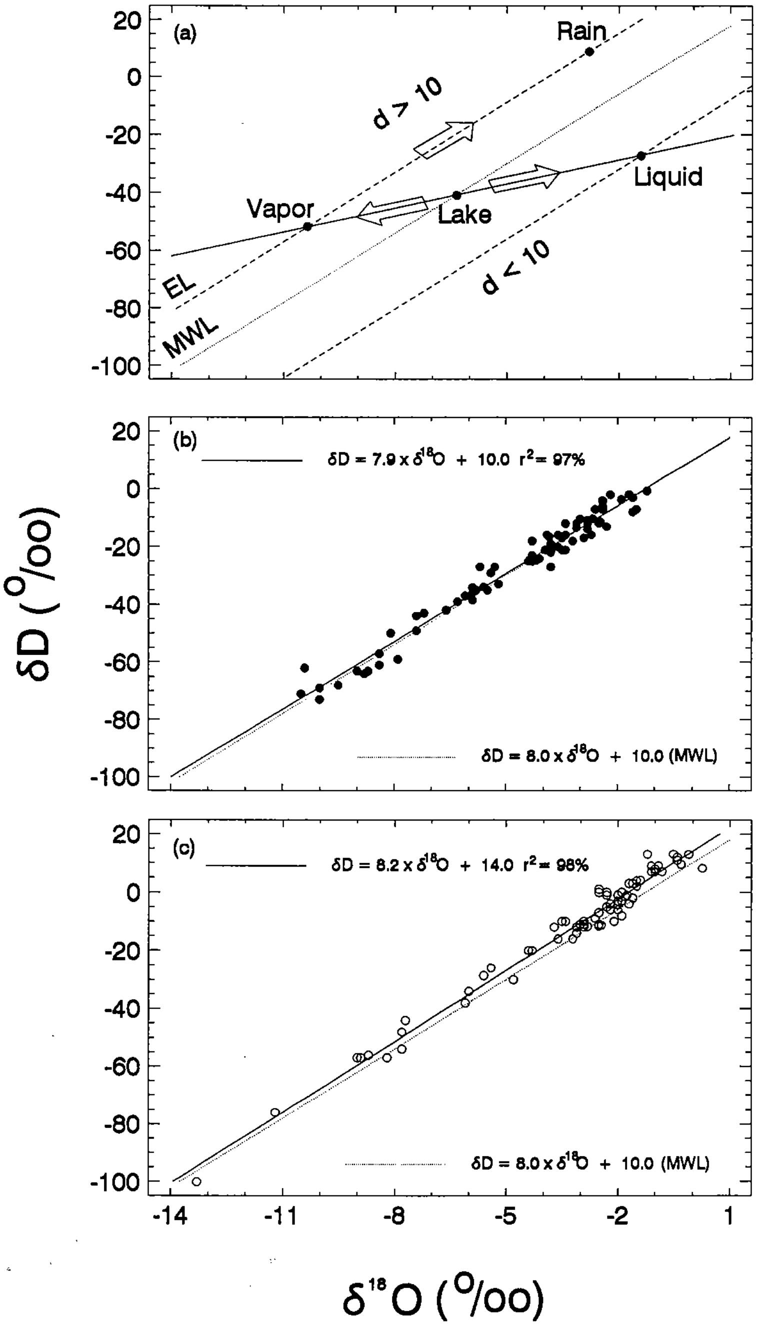


Figure 3. Plots of $\delta^{18}O$ vs δD for rainfall samples. (A) Theoretical plot showing the evolution of the water isotopic composition of a lake undergoing evaporation. The remaining water becomes progressively enriched while the vapor phase becomes depleted following a typical evaporation line (EL). (B) Monthly values for Manaus during the rainy season. Regression lines show a deuterium excess equal to 10%, coincident with the meteoric waterline (MWL). (C) Monthly values for Manaus during the dry season. Regression lines show a deuterium excess equal to 14%•, above and parallel to the meteoric waterline (MWL).

vember) there is a greater amount of energy available to promote evaporation, which is reflected by deuterium excess values consistently higher than 10‰. During the rainy season (December-May) the amount of available energy is relatively less and, as a consequence, the deuterium excess parameter remains closer to 10‰.

From the above discussion, two points arise: 1) during the rainy season, water recycling in the basin is indeed dominated by the transpirational flux, and 2) during the dry season a significant input from the evaporation of open water is a legitimate possibility. This second point has been addressed by Gat and Matsui (manuscript in preparation). In their model of the atmospheric water balance in the Amazon they estimate that the evaporative component may contribute up to 40% of the total flux of recycled water.

CONCLUSION

The findings of this study clearly indicate the importance of water recycling in the hydrological cycle of the Amazon Basin. They not only confirm the importance of forest evapotranspiration as suggested by Dall'Olio et al. (19) and Salati et al. (3, 4), they also demonstrate the important role that may be played by evaporation from open water bodies. One decade ago the importance of trees in transferring water from the soil to the atmosphere was shown. In this paper we suggest that trees may play an additional role in the Amazon water cycle, where the water storage in their lives, after precipitation events, provides an additional important source of water to the atmosphere.

Two major questions remain to be clarified in the future: 1) what is the source of the water and/or the mechanism responsible for the large discrepancy between predicted and actual data for the western part of the basin observed during the rainy season (November-April)? and 2) what is the actual contribution of direct evaporation to water recycling within the basin, and what are the relative contributions of lakes and forest canopy to the total flux of evaporation?

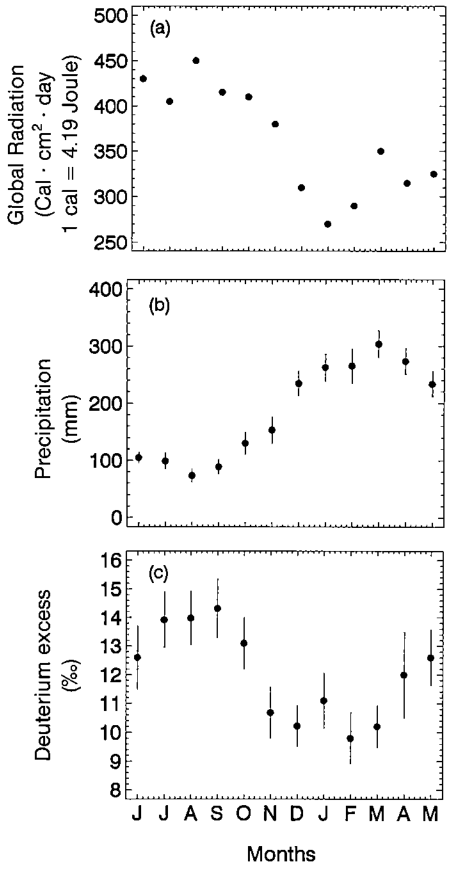


Figure 4. (a) Monthly values of the global radiation at surface measured in Manaus (25). (b) Averaged monthly values of precipitation in Manaus, from 1972 to 1986. (c) Averaged monthly values of deuterium excess in rainfall at Manaus; data from 1972 to 1986. Standard errors are represented by vertical bars.

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