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Reconstruction of the Amazon Basin Effective Moisture Availability over the Past 14,000 Years

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Quantifying the moisture history of the Amazon Basin is essential for understanding the cause of rain forest diversity and its potential as a methane source. We reconstructed the Amazon River outflow history for the past 14,000 years to provide a moisture budget for the river drainage basin. The oxygen isotopic composition of planktonic foraminifera recovered from a marine sediment core in a region of Amazon River discharge shows that the Amazon Basin was extremely dry during the Younger Dryas, with the discharge reduced by at least 40% as compared with that of today. After the Younger Dryas, a meltwater-driven discharge event was followed by a steady increase in the Amazon Basin effective moisture throughout the Holocene.

The Pleistocene climate history of Earth's equatorial regions is comparatively poorly known, particularly for the Amazon Basin. Amazon Basin glacial temperature reconstructions suggest cooler conditions during the last glacial period. Stable isotopes from Peruvian ice cores imply that Last Glacial Maximum (LGM) high-altitude temperatures were 8° to 12°C cooler than present-day temperatures (*1, 2*) (Fig. 1), and noble gases in groundwater suggest LGM lowland Brazil air temperatures that are 5°C cooler (*3*). However, Amazon Basin records of glacial moisture availability are confusing and contradictory. This is because aridity has mainly been inferred [e.g., (*4, 5*)], for example, from evaporate deposits, paleo-dunes, lake levels, pollen, and erosion proxies found in deep-sea sediments. In many cases, the proxy records are spatially limited, providing a highly localized indication of relative wetness, which cannot be quantified. In contrast, our study circumvents this problem by using adjacent marine sediment, which provides an integrated signal indicative of the moisture of a large proportion of the Amazon River drainage basin.

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Reconstructing glacial tropical aridity is essential for three reasons. First, it is a key physiological control on vegetation distribution. It is therefore essential for testing the Pleistocene tropical rain forest refuge hypothesis (*6*) and thus for understanding the immense diversity and species endemism of the Amazon Basin [e.g., (*7, 8*)]. Second, tropical wetlands, which current represent nearly 60% of the world's wetlands (*9*), represent a major source of atmospheric methane; thus, it has been suggested that glacial tropical aridity is a primary control on the ice core atmospheric methane records (*10, 11*). Unfortunately, there are no reliable estimates of the total area covered by Amazonian wetlands; however, it has been estimated that the floodplain covers at least 100,000 km^2 and that there is at least 100,000 km^2 of lakes and swamps (*9*), demonstrating the huge potential of this area for the tropical production of methane. Third, reconstructed Amazon Basin available moisture provides an indication of overall global tropical moisture and hence tropical atmospheric water vapor, another key global warming gas.

We analyzed sediments from Ocean Drilling Program (ODP) Site 942 (5°45′N, 49°6′W, water depth of 3346 m), which was drilled to the west of the Amazon Fan to provide a continuous paleo-monitoring of the mixing of Amazon River freshwater and the North Brazilian Coastal Current (NBCC) (*12, 13*). The upper 4.5 m below sea floor of sediment were sampled at an average of 5-cm intervals (~100 to 200 years). Eleven accelerator mass spectrometry radiocarbon dates (Fig. 2) on monospecific planktonic foraminifera form the basis of the age model that was calibrated to calendar years with the program CALIB 3 (*14*). The stable isotopic determination on the planktonic foraminifera *Neogloboquadrina dutertrei* is shown in Fig. 2 (*15*). *Neogloboquadrina dutertrei* is a tropical seasonal thermocline foraminifer, preferring deeper cooler waters, which thus isolate it from rapid shifts in surface water salinity due to numerous lenses of freshwater that break off from the Amazon River outflow plume (*12, 13*). Instead, *N. dutertrei* monitors the longer term mixed signal between the NBCC and the Amazon River freshwater discharge. This is demonstrated by the record of *N. dutertrei*, which has a signal of similar amplitude but with less noise as compared with that of the near-surface–dwelling *Globigerinoides ruber* (*15*). The oxygen isotopic composition ($\delta^{18}O$ record) of *N. dutertrei* from Site 942 reflects three factors: global ice volume, temperature, and the mixing ratio of isotopically depleted river water with isotopically enriched seawater.

To isolate the component of the $\delta^{18}O$ record caused by changes in the delivery of isotopically depleted Amazon River water to the site, it is necessary to subtract the ice-volume component and the local temperature change. Both of these can be removed from the *N. dutertrei* record at Site 942 by comparing them to the GeoB 3104-1 planktonic $\delta^{18}O$ record south of the Amazon River, i.e., upstream in the NBCC, before the freshwater influence (*16*). The GeoB 3104-1 temperature reconstruction (*16, 17*) shows an approximate 3° to 4°C shift in the NBCC sea surface temperature (SST) between the LGM and the Holocene and a 2°C shift between the Younger Dryas and the Holocene. Although SST estimates from planktonic foraminifera assemblages can be unreliable in the tropics [e.g., (*18*)], the SIMMAX SST reconstruction at Site 942C supports this reconstruction. After subtraction of the GeoB 3104 data, the residual changes in the *N. dutertrei* $\delta^{18}O$ record, or $\Delta\delta^{18}O$ (Fig. 2), should be a measure of changes in the magnitude of Amazon River discharge over time. A positive $\Delta\delta^{18}O$ value will be the result of a decrease in Amazon River discharge, and vice versa.

A quantitative estimate of the volume of discharge relative to the modern outflow can be calculated on the basis of the modern mixing ratio between the NBCC and the Amazon River outflow at Site 942, which is 5:1 (*19*). Presently, the isotopic difference between the Amazon River water [–5 per mil (‰) (*2, 20*)] and the

NBCC [+1‰ (*13, 16, 17*)] is 6‰. The positive values calculated for our $\Delta\delta^{18}O$ curve in Fig. 2 require either a decrease in the volume of isotopically depleted river water reaching the site, an increase in the $\delta^{18}O$ value of the river water, or some combination of the two. As a first estimate, we adjusted the $\delta^{18}O$ value of the Amazon River discharge for only the increase in $\delta^{18}O$ of water vapor associated with changes in the average $\delta^{18}O$ value of seawater, which, during the Younger Dryas, would be ~0.7‰. In this case, the enrichment of 0.5‰ in foraminifera $\delta^{18}O$ observed during the Younger Dryas represents a reduction of 55% in Amazon River discharge. However, other climate changes may have independently led to changes in the $\delta^{18}O$ value of the Amazon River that would affect this calculation. Average annual temperatures in the Amazon Basin were 4° to 5°C lower during the LGM, compared with those of today (*3*), and we infer that temperatures were probably lower by a similar amount during the Younger Dryas. This temperature decrease would have led to a decrease in $\delta^{18}O$ of the river water of ~1‰, producing a calculated Younger Dryas Amazon River discharge that is 45% of the modern value. Alternatively, the decreased precipitation would have increased the $\delta^{18}O$ value of Amazon River water through a reverse amount effect [e.g., (*2, 20*)]. For example, the relation between monthly averages of $\delta^{18}O$ and rainfall amount for Manaus, Brazil (*21*), indicates that a 50% decrease in precipitation should be associated with an increase of ~2‰ in average $\delta^{18}O$ values of precipitation. Adjusting the Younger Dryas calculated outflow for this reverse amount effect through an iterative process results in a calculated outflow that is 61% of the modern value. In Fig. 2, we use this conservative Younger Dryas calculation to provide a minimum estimate in the reduction of Amazon River outflow during the past 14,000 years (14 ky).

The reconstructed Amazon River outflow history (*N. dutertrei* $\Delta\delta^{18}O$ record) bears a striking resemblance to the Peruvian Lake Junin $\Delta\delta^{18}O$ record, another measure of effective moisture in equatorial South America (*22*). Both records show an extremely dry Younger Dryas with a sudden shift to wetter conditions at the Younger Dryas–Holocene transition and steadily increasing effective moisture levels through the Holocene (Fig. 2). The extremely dry Younger Dryas is supported by glaciological, lake, and Amazon Fan studies [e.g., (*1, 2, 23, 24*)]. The reduced Amazon River outflow is also illustrated by a marked positive deviation in both planktonic foraminifera calcite (*13*) and total organic carbon $\delta^{13}C$ that indicates a stark reduction in the Amazon discharge of dissolved organic matter enriched in ^{12}C (*25*).

The only major difference between the marine and lake moisture records is that there is an Amazon discharge event ("DE" in Fig. 2) in the *N. dutertrei* $\Delta\delta^{18}O$ record at 11,800 years ago (11.8 ka). This discharge event is also coeval with a major warming of the Andes ice sheet (*1*) and could be due to meltwater discharge. This is supported by corresponding peaks in the lithogenic/biogenic ratio and the magnetic S ratio (*4*) at Site 942. The S ratio (the ratio of isothermal remanent magnetization to saturated isothermal remanent magnetization, which measures the proportion of high-coercivity magnetic minerals to low-coercivity ferrimagnetic minerals) is particularly important because it indicates an increase in the magnetite contribution and hence deposition of more andesite from the Andes. However, the outflow estimate in Fig. 2 must be seen as an overestimation during the discharge event because any meltwater input will inject more negative $\delta^{18}O$ into the Amazon River system. However, in addition, we suggest that the discharge peak could be a combination of both Andean meltwater and an increase in precipitation, because there is insufficient ice volume from a partial melting of the Andean ice caps to account for the extent of the discharge.

Seltzer *et al.* (*22*) suggested that the variations in the effective moisture at Lake Junin could be due to the variations in the position of the Intertropical Convergence Zone (ITCZ) and the intensity of convection in the Amazon Basin. Our results indicate that these changes in aridity seen at Lake Junin are not just a local signal but are representative of a much wider area. Today, intense summer convection over the Amazon Basin results in a southward penetration of the ITCZ (*26*) (Fig. 1). This draws moist air from the Atlantic Ocean across the Amazon Basin, which brings large amounts of rainfall. It has been suggested that, during the LGM and Younger Dryas, the atmospheric circulation was more zonal [e.g., (*27*)]. This would have prevented the summer penetration of the ITCZ into the Amazon Basin and thus greatly reduced precipitation. This is shown in our effective moisture reconstruction of the Amazon Basin and supported by the model experiments of Hostetler and Mix (*28*). This hypothesis is also supported by lake data from the Bolivian Altiplano (*29*), which show an increased eastward penetration of South Atlan-

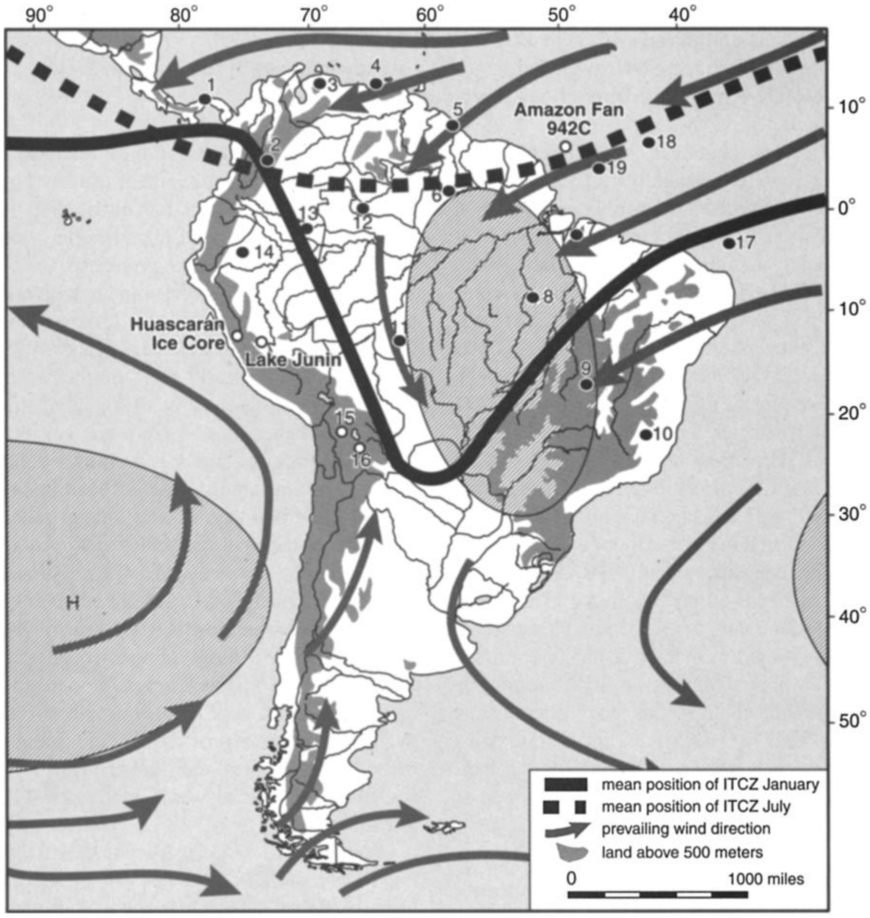

Fig. 1. Map of the present-day summer and winter locations of the ITCZ and the major wind and hence moisture sources over the Amazon Basin (*26*). Key paleoclimate studies for the Amazon Basin are shown with the following numbers: 1, El Valle; 2, Fuquene VII; 3, Lake Valencia; 4, Cariaco Trench; 5, Ogle Bridge; 6, Lake Moreiru; 7, Laggoa da Curuça; 8, Serra dos Carajás; 9, Salitre; 10, Catas Altas; 11, Rondonia; 12, Lake Pata; 13, Caquetá River; 14, Mera/San Juan Bosco; 15, Sajama ice core (*2*); 16, southern Bolivian Altiplano lakes (*29, 30*); 17, GeoB 3104-1 (*16, 17*); 18, Ceara Rise (*31*); and 19, Amazon Fan ODP Site 932 (*24*). The full references for sites 1 to 14 can be found in work by Haberle and Maslin (*24*). H, high-pressure area; L, low-pressure area.

tic and/or Pacific Ocean moisture during the Younger Dryas in direct response to the relaxation northeast of the ITCZ, as predicted (*28*). Subsequent to the Younger Dryas, the effective moisture for the Amazon Basin shows a steady increase throughout the Holocene. This increase is coeval with the intensification of Southern Hemisphere summer insolation (Fig. 2), which we suggest would lead to progressively enhanced convection and thus more penetration of Atlantic source air into the Amazon Basin, bringing with it ever increasing amounts of rainfall.

The moisture history of the Amazon Basin provides a means of assessing the tropics as a source of atmospheric methane. Not only does the Amazon Basin represent a large proportion of the world's tropical methane-producing wetlands, it also seems that its climatic response is indicative of much of the rest of the equatorial and Southern Hemisphere tropics [e.g., (*28*)]. There are three main sources that can contribute to the atmospheric methane variations recorded in the ice cores (Fig. 2): low-latitude tropical wetland and peat development, high-latitude temperate wetland and peat development, and gas hydrate release [e.g., (*10, 11*)]. Our record of Amazon Basin discharge suggests an extremely dry Younger Dryas, with discharge decreased by at least 60% of the present flow. This reduced moisture availability, in combination with reduced temperatures, would have reduced the area covered by methane-producing wetlands and contributed to the corresponding sharp drop in atmospheric methane (*10, 11*). The 40% increase in Amazon River discharge at the end of the Younger Dryas (ignoring the Amazon discharge event) corresponds to the rapid increase in the atmospheric methane record and supports its possible tropical wetland origin (*10, 11*). Interestingly, the Amazon Basin effective moisture availability is greatest at present; however, this does not necessarily correspond to the greatest methane production, as this is controlled by vegetation type and extent. It is possible that the post–Younger Dryas period with the first substantial rise in moisture and extensive flooding of the Amazon River flood plain, due to elevated sea level, created the most extensive wetlands and hence methane production. There is no corresponding change in the Amazon Basin effective moisture availability at 9 ka, when the methane record drops by over 100 parts per billion by volume. This suggests that the methane record should still be regarded as a complex signal with varying contributions from other sources.

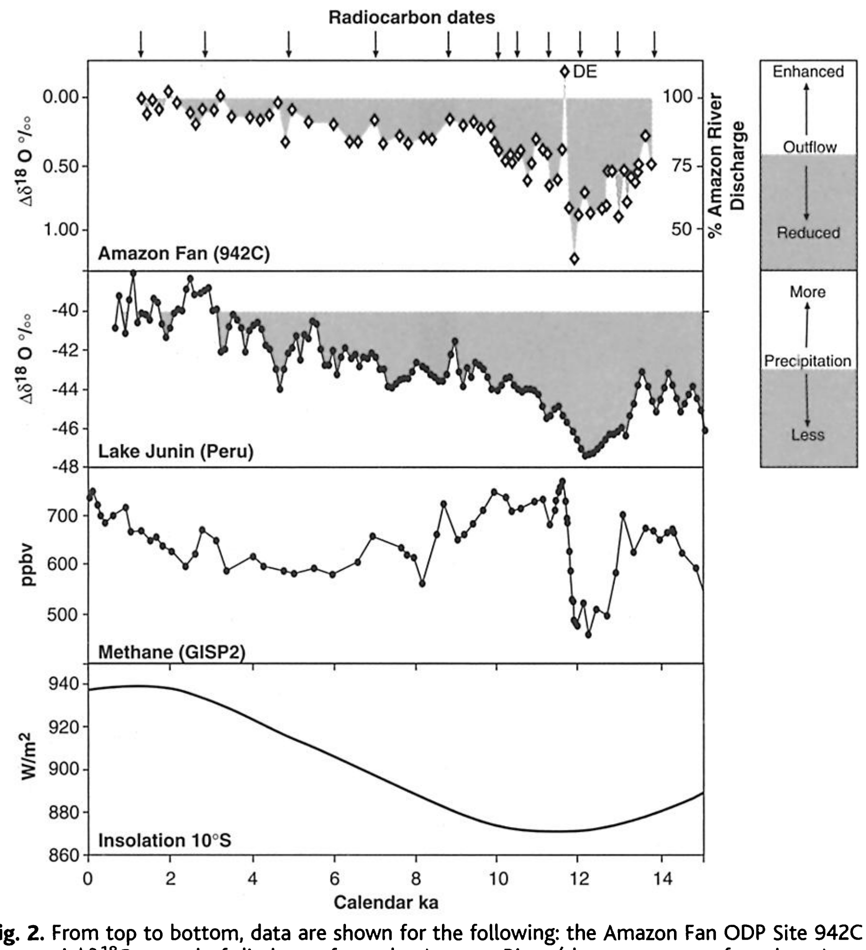

Fig. 2. From top to bottom, data are shown for the following: the Amazon Fan ODP Site 942C *N. dutertrei* $\Delta\delta^{18}O$ record of discharge from the Amazon River (the percentage of modern Amazon River discharge is the conservative Younger Dryas estimate), the Peruvian Lake Junin $\Delta\delta^{18}O$ record of effective moisture (*22*), the Greenland Ice Sheet Project 2 (GISP2) ice core atmospheric methane record [e.g., (*10, 11*)], and the summer insolation changes at 10°S (*32*). ppbv is parts per billion by volume and calendar ka indicates the age at thousand calendar years ago.

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