Amazon River Discharge and Climate Variability: 1903 to 1985

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Reconstruction of an 83-year record (1903 to 1985) of the discharge of the Amazon River shows that there has been no statistically significant change in discharge over the period of record and that the predominant interannual variability occurs on the 2- to 3-year time scale. Oscillations of river discharge predate significant human influences in the Amazon basin and reflect both extrabasinal and local factors. Cross-spectrum analyses of Amazon flow anomalies with indicators of the El Niño–Southern Oscillation phenomenon suggest that the oscillations in the hydrograph are coupled to the tropical Pacific climate cycle.

LAND-USE PATTERNS IN THE AMAZON basin are changing rapidly (*1*). Potential consequences include modifications in the basin's convective rainfall regime, where approximately 50% of the 2500-mm mean annual precipitation is recycled via evapotranspiration (*2*) and downstream changes in river flow and nutrient and sediment transport (*3*). Although there is considerable speculation (*4*), few data are available on the effects of disturbances on the hydrological cycle of the Amazon. Because of the heterogeneous nature of precipitation and precipitation collectors, river discharge is a robust integrator of the long-term hydrologic properties of a drainage basin. Gentry and Lopez-Parodi (*5*) concluded from a 1962 to 1978 record of stage (level of water surface above a reference point) of the Amazon at Iquitos, Peru, that the height of the annual flood crest had increased because of deforestation in the Andes. This interpretation has been questioned, however, on procedural and statistical grounds (*6*).

In the Amazon, as elsewhere, natural oscillations in the hydrological cycle and the processes influencing those oscillations must be distinguished before possible anthropogenic impacts can be truly attributed. For example, the El Niño–Southern Oscillation (ENSO) phenomenon in the tropical Pacific Ocean, which has been linked to climate anomalies and river flow worldwide (*7*), is one potential source of natural variability in the Amazon basin. We have analyzed a record of the oscillations in the discharge regime of the Amazon River over a time period of sufficient length to characterize the frequency of variability: the daily record of the stage of the Rio Negro at Manaus over the period 1903 to 1985 (Fig. 1). The Manaus record represents an 83-year integration of runoff and ultimately climatic conditions over 3×10^6 km^2 of the Andean and western Amazon watershed. This is the only long-term hydrological record available for the Amazon basin; systematic collections of climatological and river discharge data elsewhere in the basin were initiated in the early 1970s.

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The Manaus gage provides an accurate, long-term record of stage; it has been maintained at the same site by Manaus Harbor Ltd./Portobrás over the period of record, and movement of the river bed in the low-sediment Rio Negro (*8*) has most likely been minimal [compare with (*6*)]. To use this record as a proxy for the discharge of the Amazon River itself, the stage at Manaus must be quantitatively related to the stage of the Amazon (*9*). The Departmento Nacional de Águas e Energia Elétrica (DNAEE) has maintained a gaging station at Manacapurú (Fig. 1) since 1973. We regressed the Manaus and Manacapurú records of 1973 to 1985 and adapted existing rating curves for Manacapurú (*10*) to the Manaus stage record (*11*).

The most striking features of Amazon River discharge are its magnitude and its highly damped hydrograph (Fig. 2A). On the basis of the Rio Negro record, the mean discharge at Manacapurú for the period 1903 to 1985 was 94,600 m^3/s, which is about half of the mean annual discharge at the mouth of the Amazon (~200,000 m^3/s) and is equivalent to 10% of the world's river input to the oceans. Variability of the Amazon hydrograph is dominated by the annual cycle, with the minimum and maximum flows on record differing only by a factor of 3. Minimum discharge at Manacapurú varied between 48,000 and 84,000 m^3/s and maximum discharge between 100,000 and 140,000 m^3/s.

To reveal the nonseasonal variability of the Amazon hydrograph more clearly, we removed the long-term mean annual cycle

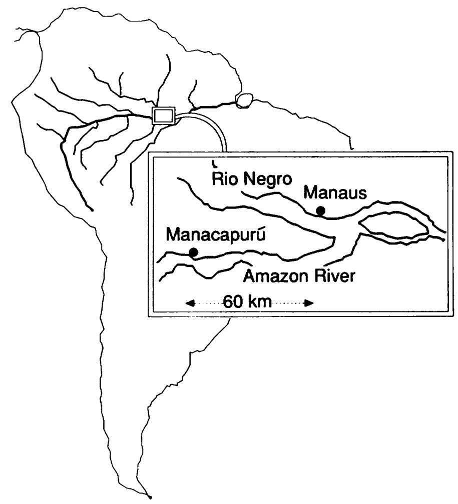

Fig. 1. Overview of the Amazon basin and its major tributaries, with the locations of the Manaus and Manacapurú river-stage gages indicated in the inset. The Amazon is known as the Rio Solimões above its confluence with the Rio Negro.

(*12*), producing a deseasonalized hydrograph (Fig. 2B). Over the period 1903 to 1926, there were pronounced oscillations about the mean, and the differences between minima and maxima of deseasonalized discharge were 30,000 to 40,000 m^3/s. The minimum anomaly on record, −45,000 m^3/s in 1926, has been attributed to a period of extensive drought and fires (*13*). From 1927 to 1962, the oscillations exhibited a comparable frequency, with reduced amplitude of 10,000 to 20,000 m^3/s. Near the end of a secular trend of increasing discharge, which began around 1963, the maximum anomalies on record, 30,000 m^3/s in 1973 and again in 1976, were obtained. This period corresponds to that reported by Gentry and Lopez-Parodi (*5*). Thereafter, however, discharge returned to its long-term mean value. Power spectrum analysis of the deseasonalized hydrograph reveals a pronounced spectral peak at 2.4 years (Fig. 3A). The tendency for regular oscillations on the 2- to 3-year time scale is evident in the deseasonalized time series itself (Fig. 2B). Similarly, recurrence intervals are dominated by the 2- to 3-year flows (*14*). The deseasonalized hydrograph exhibits no significant linear trend over the period of record (*15*).

Climate records (*16*) and general circulation model calculations (*17*) suggest that interannual variations in the precipitation regime and hence discharge of the Amazon may be linked to changes in the general circulation of the atmosphere over the tropical Pacific Ocean associated with the ENSO phenomenon. To test this hypothesis, we compared the river discharge anomalies to

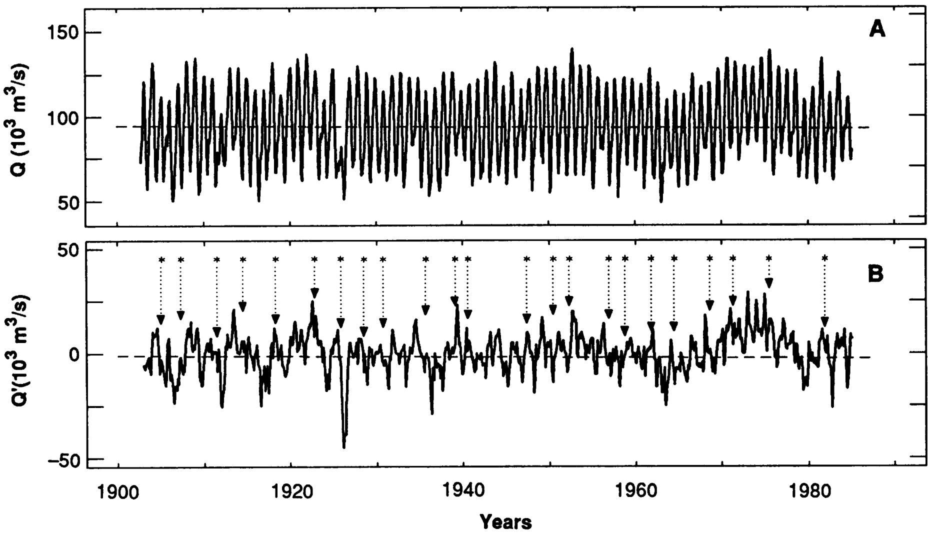

Fig. 2. Discharge of the Amazon River at Manacapurú; (**A**) discharge time series, 1903 to 1985; (**B**) deseasonalized Q' hydrograph, 1903 to 1985. Arrows indicate occurrence of ENSO events.

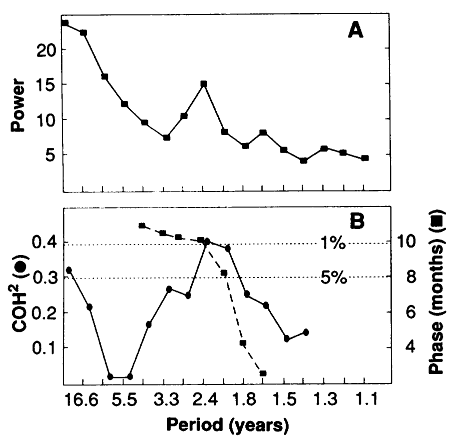

Fig. 3. Spectral analysis of the deseasonalized Amazon discharge record, 1903 to 1985. The abscissa is linear in frequency (per year), but not in period. (**A**) Power spectrum, normalized so that the total variance is unity; (**B**) coherence (COH) spectrum and phase lag between Darwin pressure and Amazon discharge based on deseasonalized monthly means for the period 1903 to 1985. Upper and lower dashed horizontal lines represent the 5% and 1% significance levels, respectively, for the coherence spectrum.

atmospheric pressure anomalies at Darwin, Australia, a widely used index of the ENSO (*18*), for the time period 1903 to 1985 (*19*). Qualitatively, the months of maximum pressure anomalies (Southern Oscillation negative phase) corresponding to ENSO warm events preceded the negative flow anomalies in most cases (Fig. 2B). Major ENSO events, for example 1925 to 1926 and 1982 to 1983, are reflected in pronounced low discharges. The converse effect, high discharge associated with the Southern Oscillation positive phase, is also apparent. The unusually cold waters of the eastern Pacific in 1989 (*20*) are also being accompanied by high discharge in the Amazon (*21*).

To calculate the statistical significance of these observations, we performed cross-spectral analysis between the deseasonalized Amazon and Darwin records (*22*). The Southern Oscillation is manifest by a broad peak in the Darwin pressure power spectrum that extends over 2- to 10-year periods (*23*). The coherence-square between the Amazon discharge and Darwin pressure was significant at the 5% level at two spectral estimates in the 2- to 3-year period range. The associated phase relation indicates that minimum discharge lags maximum pressure anomalies by about half a year. As a further test, we also performed cross-spectral analysis between monthly mean sea-surface temperature in the eastern and central equatorial Pacific, a key oceanic indicator of ENSO, and Amazon discharge for the period 1946 to 1985. The coherence square for this pair of variables also exceeded the 5% confidence level in the 2- to 3-year period range (not shown). In a linear regression analysis based on shorter records, Molion and Moraes (*24*) found that the discharge regime of the Rio Trombetas (eastern Amazônia) was correlated with ENSO. We conclude from these results that the variability in the Amazon hydrograph on 2- to 3-year time scales is coupled to the ENSO cycle.

The oscillations of river discharge predate significant human influences in the Amazon basin and reflect both extrabasin and local factors. Our analysis is evidence of the long-term linkage of extrabasin atmospheric circulations on Amazon discharge, but it does not shed light on the actual physical mechanisms involved. Several authors (*16, 24*) have suggested that the descending branch of zonal circulation over the equatorial Pacific could be shifted eastward over Amazônia during the Southern Oscillation negative phase, leading to a suppression of convection and hence of precipitation, while the ascending motions associated with the Southern Oscillation positive phase would be strengthened, promoting increased precipitation over Amazônia and northeastern Brazil. However, only a portion of the variance in the discharge regime is linked to the ENSO phenomenon. Relations between runoff and precipitation are complicated partly because of the carry-over storage ("basin-memory effects") typical of large catchments. Local climate influences, such as the boundary layer convergence mechanisms and the steady progression of individual fronts and air mass boundaries characteristic of the region (*25*), contribute to discharge variability.

With regard to the postulated effects of Andean deforestation (*5*), there was indeed an increase in flow from 1962 to 1978, but this increase appeared to be within the range of longer term cycles. Considerable caution, particularly with the use of short-term records over large areas, must be exercised in determining anthropogenic impacts in large forested tropical basins. Conversely, it would be difficult to identify a clear deforestation effect in the highly damped discharge regime of the Amazon River mainstem. The likelihood of linkages between the Amazon basin and large-scale atmospheric circulations reinforces the importance of determining the factors controlling the hydrology of the basin in the face of extensive land-use change.

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purú was then calculated from combining this regression with the rating curve (10) to obtain the flux in cubic meters per second $Q = 30{,}683 - 9.72\ S_{mc} + .016\ S_{mc}^2$, which was reported as monthly mean discharge.
12. A deseasonalized hydrograph was calculated by subtracting the 83-year mean discharge for each month (Q^*) from the respective monthly mean discharge in each year (Q) for the ith month of the jth year to form the deviation from the long-term monthly mean discharge $Q'_{i,j} = Q_{i,j} - Q_i^*$.
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Flood Basalts and Hot-Spot Tracks: Plume Heads and Tails

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Continental flood basalt eruptions have resulted in sudden and massive accumulations of basaltic lavas in excess of any contemporary volcanic processes. The largest flood basalt events mark the earliest volcanic activity of many major hot spots, which are thought to result from deep mantle plumes. The relative volumes of melt and eruption rates of flood basalts and hot spots as well as their temporal and spatial relations can be explained by a model of mantle plume initiation: Flood basalts represent plume "heads" and hot spots represent continuing magmatism associated with the remaining plume conduit or "tail." Continental rifting is not required, although it commonly follows flood basalt volcanism, and flood basalt provinces may occur as a natural consequence of the initiation of hot-spot activity in ocean basins as well as on continents.

CONTINENTAL FLOOD BASALTS occur worldwide (Fig. 1), and because of their wide age distribution and enormous volume, they are of fundamental importance in the recent evolution of the continental crust and lithosphere. However, the basic cause (or causes) of flood basalt eruptions has remained a mystery. In developing his theory that fixed hot spots (such as Hawaii and Iceland) were formed from convective mantle plumes, Morgan (*1, 2*) noted that hot spots were associated with flood basalts and suggested that flood basalts occurred at the initiation of mantle plume activity. Indeed, laboratory experiments (*3*) have shown that a large initial diapir or "head" is necessary in order to establish a mantle plume conduit (Fig. 2). Recently, several workers have suggested that the eruption of the Deccan flood basalts in India marked the onset of activity of the Reunion hot spot (*4–6*). In this report we show that many continental flood basalt events and, perhaps, large suboceanic plateaus could be the result of mantle plume initiation. Further, we show that the plume initiation model provides a plausible explanation for the enormous volcanic eruption rates for flood basalts compared to those for the associated hot-spot tracks.

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Many flood basalt provinces occur along continental margins and were associated with initiation and early development of continental rifting (*7–12*). The best preserved provinces are predominantly Mesozoic and younger in age. The largest of these events (Deccan, North Atlantic, Parana, and Karoo) were coincident in space and time with the earliest activity of major hot spots (Reunion, Iceland, Tristan da Cunha, and Marion, Fig. 1). If these flood basalts and hot-spot tracks resulted from a common mantle-plume formation mechanism, there should be a fairly consistent relation between the size of the initial plume head or diapir (represented by flood basalt volume) and the rate of flow through the remaining deep-mantle conduit (represented by hot spot–track volcanism). To test this idea, we have estimated volumes and eruption rates (Table 1) for several well-studied flood basalt provinces and associated hot spots.

The Deccan Traps, a thick sequence of flat-lying basalt flows covering nearly 500,000 km^2 of west-central India (*10*), is associated with the Reunion hot spot. At its greatest thickness (in the Western Ghats) the lava flow succession is over 2000 m (*12*). When correlative basalts identified offshore (Arabian Sea) are included and an estimate is made for eroded lavas, the province may have covered more than 1.5×10^6 km^2 (*5, 13, 14*). Several lines of evidence indicate that most of the basalt was erupted rapidly. Interflow sedimentary beds, evidence of extensive weathering, and erosional unconformities are scarce in much of the province (*10*). The flows are predominantly reversely magnetized and only two polarity reversals (normal to reverse to normal) have been identified in the entire sequence (*5*). Recent ^{40}Ar-^{39}Ar incremental heating ages show that volcanism occurred between 65 and 69 million years ago (Ma) (*15*) and that the 2000-m-thick Western Ghats section was erupted in less than 2 million years (*16*). In consideration of all evidence for the duration of volcanism, most of the Deccan basalts may have accumulated in as little as 0.5 million years (*17*). The average eruption rate would then have been greater than 1 km^3 per year; more likely, episodes of more rapid eruption were separated by inactive periods (*14*). A series of southward-younging submarine volcanic lineaments (the Laccadive, Chagos, and Mascarene ridges) link the Deccan flood basalts to the Reunion hot

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