JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. D12, PAGES 14,189–14,198, JUNE 27, 1999

Trends in the hydrologic cycle of the Amazon basin

Marcos Heil Costa[1] and Jonathan A. Foley

Climate, People and Environment Program (CPEP), Institute for Environmental Studies
Department of Atmospheric and Oceanic Sciences, University of Wisconsin, Madison

Abstract. Although previous studies have considered the long-term variability of precipitation and river discharge in the Amazon basin, other components of the hydrologic cycle, such as evapotranspiration and the transport of water vapor, have not received the same attention. This study examines the 20-year variability of the full hydrologic budget of the Amazon basin, using a 1976–1996 time series from the National Centers for Environmental Protection/National Center for Atmospheric Research reanalyzed meteorological data set. Within this 20-year record, there is a statistically significant decreasing trend in the atmospheric transport of water vapor both into and out of the Amazon basin. This trend is associated with a general relaxation of the southeasterly trade winds, a weakening of the east-to-west pressure gradient, and a warming of the sea surface temperatures in the equatorial South Atlantic region. While the atmospheric transport of water vapor through the Amazon basin has decreased, the internal recycling of precipitation within the basin increased and basin-wide precipitation, evapotranspiration, and runoff have remained nearly constant. Even though basin-average precipitation and runoff have remained fairly stable, other components of the Amazon basin's hydrologic cycle have been altered significantly by large-scale changes in atmospheric circulation.

1. Introduction

The Amazon basin has received considerable attention from the scientific community, largely because of the important ecosystems and natural resources that reside there. In addition, the Amazon is one of the major tropical heating centers that fuels the general circulation of the atmosphere. Numerous modeling studies have examined how the climate and hydrological systems of the basin may respond to human activities, including land use and deforestation (see review by *Lean and Rowntree* [1997]). However, in order to evaluate possible anthropogenic perturbations to the Amazonian environment we must first improve our understanding of the natural climatic and hydrological processes operating within the basin.

Precipitation patterns within Amazonia exhibit strong variations from year to year. Some of this variability, especially in northern Amazonia, is related to the El Niño-Southern Oscillation (ENSO) [*Kousky et al*., 1984; *Richey et al*., 1989; *Marengo*, 1992]. However, ENSO is actually not the dominant driver of precipitation extremes in much of Amazonia [*Marengo and Hastenrath*, 1993; *Neves*, 1995]. Other important drivers of precipitation variability include the strength of the North Atlantic high, the position of the intertropical convergence zone (ITCZ), and sea surface temperatures in the tropical Atlantic. While numerous authors have examined interannual variability in Amazonian climate, only a few studies have considered longer-term modes of variability, using rainfall and hydrological records.

The use of river discharge records as indicators of climate change have several advantages and disadvantages: changes in land use may increase or decrease the streamflow; construction of dams may increase evaporation and is likely to change the seasonality of the river; diversion of flow to irrigated lands also decreases the streamflow; and gradual changes in river bed formation through erosion or sediment deposition may be ignored in calculating the rating curves used to estimate discharge form the water level [*Marengo et al*., 1998]. On the other hand, hydrologic records of streamflow have the advantage of integrating spatial variability within the basin scale and is a good alternative when the rain gauge density is very low [*Richey et al*., 1989; *Lettenmaier et al*., 1994].

Gentry and Lopez-Parodi [1980] reported an increase in flood frequency in the Ucayali (Amazon) River at Iquitos (Peru) during a period when there were no significant changes in precipitation (1962–1978). However, these results were challenged by *Richey et al*. [1989], who showed that the Amazon River discharge at Manacapuru (downstream of Iquitos) did not exhibit any significant increase during the entire 83-year period between 1903 and 1985.

In a more comprehensive study, *Rocha et al*. [1989] tested two Amazonian River discharge and several precipitation records for indications of decadal-scale and long-term variability. They concluded that many precipitation and discharge records contained increasing trends during the 1960s and early 1970s. However, the discharge and rainfall records returned to their long-term average values in the late 1970s and 1980s. One possible explanation for this behavior may be associated with changes in the frequency and duration of the positive phase of the Southern Oscillation [*Molion*, 1990]. During the interval between 1961 and 1976, 11 out of the 16 years had below normal sea surface temperatures in the equatorial Pacific between 90° and 160°W.

Using a set of rainfall time series between 15 and 62 years long, *Paiva and Clarke* [1995] found statistically significant trends in rainfall for the eastern (decreasing rainfall) and western (increasing rainfall) portions of the Amazon basin. In ad-

[1]Permanently at Departamento de Engenharia Agrícola, Universidade Federal de Viçosa, Viçosa, Brazil.

Paper number 1998JD200126.
0148-0227/99/1998JD200126$09.00

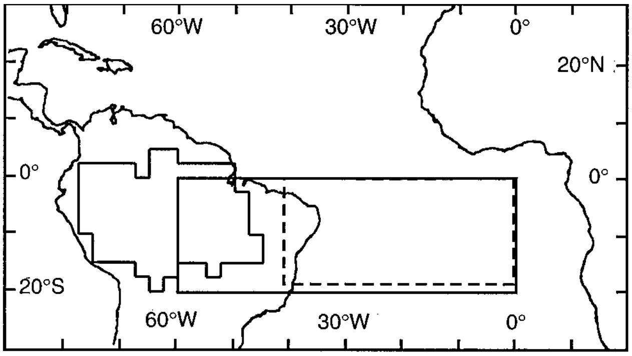

Figure 1. Orientation map. The Amazon basin is represented on a 2.5° × 2.5° grid. The solid line rectangle refers to the area presented in Figures 6 and 7. The dashed line rectangle refers to the area presented in Plate 1.

dition, *Chu et al.* [1994] reported that 15-year-long records of satellite-based outgoing longwave radiation (OLR) measurements show a significant decrease in OLR over time, which may indicate an overall increase in atmospheric convection over the basin. *Chu et al.* [1994] also reported an increasing trend in precipitation at Belém and Manaus.

Marengo [1995] studied the long-term variability of hydrological records of several South American rivers, including a 90-year-long time series of the Negro River water level at Manaus, in the May–July season. For this river he concluded that the time series did not reveal significant (at the 10% level) trends over the period of recordings. He also remarked that there was an increase in the river levels from 1970 to 1980, but this increase is within the range of long-term cycles. However, *Curtis* [1998] analyzed the same time series for the period 1958–1996 and concluded that the series (relative to the months of January, February, and March) show an upward trend significant at the 5% level; no significant trends were found in the other months' series.

More recently, *Marengo et al.* [1998] used the Mann-Kendall test to evaluate trends in river discharges (3 months of highest flow) in 8 points in the Amazon basin, where the length of the time series varied between 22 and 90 years. They found no significant (at the 5% level) trends in all records tested. They also tested the trends in the rainfall records of several stations in Amazonia in the three wettest months. All the series considered have at least 70 years of data. They concluded that the records do not present any significant trend at the 5% level.

While the aforementioned studies have examined the long-term variability of precipitation and river discharge in the Amazon basin, the other components of the hydrologic cycle, such as evapotranspiration and atmospheric water vapor transport, have not received the same level of attention. Considering all of the components of the hydrologic cycle together can considerably improve our understanding of the Amazon's water cycle.

Here we analyze the behavior of the Amazon's hydrological cycle using 20 years (1976–1996) of reanalyzed meteorological data from the National Centers for Environmental Protection (NCEP)/National Centers for Atmospheric Research (NCAR) data set [*Kalnay et al.*, 1996]. This reanalyzed meteorological data set was constructed by assimilating a variety of land surface, ship, rawinsonde, pibal, aircraft, satellite, and other quality-controlled data in a state-of-the-art numerical weather forecast and analysis system. The NCEP/NCAR data set includes estimates of precipitation, evapotranspiration, runoff, atmospheric humidity, and winds, allowing us to construct a full three-dimensional water vapor budget of the basin.

2. NCEP/NCAR Reanalysis Data

Reanalyzed meteorological data sets have many advantages over other, more traditional data sets, including (1) most of the variables are internally consistent, obeying the basic physical laws of the numerical forecast model (except for land surface water fluxes; see below), and (2) the quality of the data is controlled, eliminating discontinuities in the record associated with changes in the data assimilation system and data containing gross instrumental or human errors. However, because the reanalysis procedure combines raw observations with numerical model analyses of the atmosphere, there may be model-dependent biases in the data set [*Kalnay et al.*, 1996]. Furthermore, some variables in the data set are entirely derived from the model (e.g., latent heat flux) and therefore may include a more significant bias than variables that are based on primary measurements (e.g., wind speed and humidity).

In the NCEP/NCAR reanalysis, surface variables are available on a T62 Gaussian grid (1.875° × 1.905° resolution), and atmospheric data are available on a 2.5° latitude by 2.5° grid longitude, with 17 levels in the vertical. To construct a hydrologic budget of the Amazon basin (Figure 1), we use a variety of surface data, including monthly mean precipitation, latent heat flux (evapotranspiration), and surface runoff. In addition, we use the atmospheric data necessary to calculate the column-integrated advection of water vapor: monthly means of zonal and meridional wind speed (u and v), specific humidity (q), and the correlations between them ($u'q'$ and $v'q'$), from 1000 to 300 hPa (8 levels).

One serious disadvantage of the NCEP/NCAR data set for hydrologic studies, however, is that the soil moisture values were numerically restored (over several months) toward a baseline climatological value [*Mintz and Serafini*, 1992]. This procedure acted as a source or sink of water to the soil (see section 4) and also reduced the interannual variability of the soil-related water fluxes [e.g., *Roads et al.*, 1999]. Implications of this procedure to our analyses are discussed in the following sections.

To evaluate the accuracy of the NCEP/NCAR data set in the Amazon basin, we have compared some of the data to other

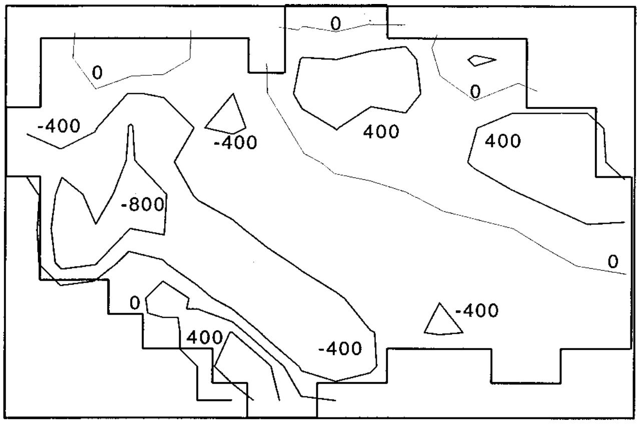

Figure 2. Imbalance of the surface water budget ($P - E - R$) averaged over 20 years.

data sets: the NASA Goddard Space Flight Center (GSFC) Data Assimilation Office (DAO) reanalyzed data set [*Schubert et al*., 1993] was used to evaluate the atmospheric water vapor transport and evapotranspiration estimates; the EOS-Amazon precipitation data sets was used to evaluate trends in precipitation. In a previous study we compared six different precipitation data sets, including the NCEP/NCAR data set, over the Amazon basin [*Costa and Foley*, 1998].

3. Methods

In this study we have constructed an annual-average hydrologic budget of the Amazon basin for each hydrological year between 1976 and 1996. All annual-average data are organized in terms of the Amazon's hydrological year (starting on September 1st and ending on August 31st), so that the rainy season is not divided in two. In order to calculate the annual water balance we use monthly mean values of precipitation, latent heat flux (evapotranspiration), and surface runoff at each grid cell within the basin. In addition, we calculate the column-integrated transport of water vapor, using zonal and meridional wind speed ($\bar{u}$ and $\bar{v}$), specific humidity ($\bar{q}$), and their covariance ($\overline{u'q'}$, $\overline{v'q'}$) at the levels 1000, 925, 850, 700, 600, 500, 400, and 300 hPa. These levels are adequate for the calculation of water vapor fluxes because water vapor is mostly concentrated at the lower levels. Spatially integrating these fluxes over the entire basin, we calculate the following basin-averaged hydrological budget terms for each year: average precipitation (P), average evapotranspiration (E), average runoff (R), water vapor input (I), water vapor output (O), and water vapor convergence (C, where $C = I - O$).

Table 1. Estimates of Evapotranspiration for the Amazon Basin

Source	E, mm d^{-1}	Method	Notes
Molion [1975]	3.1	climatonomical	30 years
Villa Nova et al. [1976]	3.2	Penman	30 years
Korzun [1978]	3.5	Budyko	···
Marques et al. [1980]	3.5	atmospheric water balance	1 year
Willmott et al. [1985]	3.3		
Matsuyama [1992]	3.1	atmospheric water balance	1 year (FGGE)
Eltahir and Bras [1994a]	3.1	ECMWF assimilated data	6 years
Vörösmarty et al. [1996]	3.3	Thornthwaite	5 years
Rao et al. [1996]	4.5	atmospheric water balance	ECMWF assimilate data, 5 years
Costa and Foley [1997]	3.7	land-surface model	driven by 30-year climatologies
NASA GSFC	4.6	reanalyzed data	8 years
NCEP/NCAR (before correction)	4.3	reanalyzed data	20 years
NCEP/NCAR (after correction)	3.8	reanalyzed data	20 years

FGGE, First Global Atmospheric Research Program (GARP) Global Experiment; ECMWF, European Centre for Medium-Range Weather Forecasts; GSFC, Goddard Space Flight Center; NCEP-National Centers for Environmental Protection; and NCAR-National Center for Atmospheric Research.

Table 2. Estimates of Runoff for the Amazon River

Source	Site	Discharge, 10^3 m^3 s^{-1}	Runoff, mm yr^{-1}
UNESCO [1978]	Óbidos	157	1060
Milliman and Meade [1983]	mouth	200	1024
Vörösmarty et al. [1989]	Óbidos	170	1160
Russell and Miller [1990]	mouth	200	1086
Mintz and Serafini [1992]	mouth	190	965
Matsuyama [1992]	Óbidos	155	1054
Matsuyama [1992]	Amazon at Óbidos + Xingu	164	1014
Oki et al. [1995]	Óbidos	···	1053
Vörösmarty et al. [1996]	Óbidos	···	1086
Costa and Foley [1997]	Óbidos	162	1106
This study	mouth	···	937

The input of water vapor at each grid cell I' is computed using (1), following *Peixoto and Oort* [1993, p. 274]:

$$I' = \frac{\Delta y}{gA} \int_{300}^{P_{\text{sfc}}} (\bar{u}\bar{q} + \overline{u'q'})\, dp$$

or (1)

$$I' = \frac{\Delta x}{gA} \int_{300}^{P_{\text{sfc}}} (\bar{v}\bar{q} + \overline{v'q'})\, dp$$

where A is the area of the Amazon basin, g is the acceleration due to gravity, and Δx and Δy are the length of the zonal and meridional grid cell boundaries, respectively. The total input to the basin I is the sum of the inputs in all grid cell boundaries. The output O is calculated similarly. The convergence C is computed from the difference $I - O$.

We estimate the basin-wide precipitation recycling ratio (ρ) using

$$\rho = \frac{E}{E + I} \tag{2}$$

derived from the expression used by *Eltahir and Bras* [1994a], which assumes that water vapor is well mixed in the atmosphere. Despite the data from the Atmospheric Boundary Layer Experiment (ABLE) [*Harris et al*., 1988] supporting this assumption, there is still some controversy about this issue.

Although we acknowledge that the well-mixed assumption may not be satisfied everywhere, it is our opinion that ρ is a stronger estimator of the precipitation recycling ratio than others used before. Moreover, if ρ is not an unbiased estimator of the precipitation recycling ratio, at least it is a good estimator of the proportion of local sources of water vapor to the total sources of water vapor to the basin.

4. Climatological Water Balance

In a balanced hydrological system the long-term rate of precipitation equals the sum of evapotranspiration and runoff

Table 3. Time Series and Climatologies of the Components of the Hydrologic Cycle in the Amazon Basin After the Correction

Hydrological Year	P, mm	E,7 mm	R, mm	I, mm	O, mm	C, mm	ρ	$I + E - P - O$, mm	$P - E - R$, mm	$C - R$, mm
1976–1977	2127	1328	794	3434	2678	757	28%	−43	5	−38
1977–1978	2351	1319	990	3374	2442	932	28%	−100	42	−59
1978–1979	2250	1307	891	3109	2115	994	30%	51	52	103
1979–1980	2287	1325	943	3526	2583	943	27%	−20	19	0
1980–1981	2329	1295	990	3344	2315	1030	28%	−4	44	40
1981–1982	2193	1365	900	3475	2603	872	28%	44	−72	−29
1982–1983	2427	1458	960	3519	2524	995	29%	26	9	34
1983–1984	2585	1436	1102	3534	2432	1102	29%	−47	47	0
1984–1985	2456	1438	1046	3442	2450	992	30%	−26	−28	−54
1985–1986	2375	1418	1005	3217	2256	960	31%	3	−48	−45
1986–1987	2297	1452	870	3266	2471	795	31%	−50	−25	−76
1987–1988	2271	1420	869	3137	2389	748	31%	−103	−18	−120
1988–1989	2546	1401	1077	3170	2045	1125	31%	−20	68	48
1989–1990	2490	1442	988	3280	2242	1038	31%	−10	60	50
1990–1991	2459	1431	1056	3208	2220	988	31%	−40	−28	−68
1991–1992	2285	1451	927	3213	2448	765	31%	−69	−93	−162
1992–1993	2244	1435	891	2998	2261	737	32%	−72	−82	−154
1993–1994	2151	1349	833	3193	2421	772	30%	−30	−31	−61
1994–1995	2159	1314	810	2946	2146	800	31%	−45	35	−11
1995–1996	2150	1302	804	2710	1952	758	33%	−90	44	−46
Long-term average	2322	1384	937	3255	2350	905	30%	−32	0	−32

We report estimates of basin-average precipitation (P), evapotranspiration (E), runoff (R), water vapor input (I), water vapor output (O), water vapor convergence ($C = I - O$), and precipitation recycling (ρ) for each hydrological year from 1976 to 1996. The last three columns show the imbalance in the atmospheric, surface, and atmospheric + surface levels, respectively.

($P = E + R$). However, analyzing the land-surface hydrological budget terms in the NCEP/NCAR data set, we find that there is a small imbalance. Long-term basin-average precipitation (P) minus evapotranspiration and runoff ($E + R$) is -179 mm yr^{-1}, suggesting a source of water inside the basin, which, we believe, was artificially added during the reanalysis procedure (see discussion in section 2). A map of this residual (Figure 2) shows that its value is not constant, and in parts of the basin it is actually acting as sink of water. This artificial addition of water to the soil during the reanalysis procedure could cause an increase in the rates of evapotranspiration

Table 4. Estimates of Annual Precipitation for the Amazon Basin

Source	Series Span	Series Length, years	Estimate, mm yr^{-1}
Leemans and Cramer [1990]	1930–1960	30	2126
Legates and Willmott [1990]	1920–1980	up to 60	2166
Russell and Miller [1990]	1950–1979	30	1900
Global Precipitation Climatology Project [*Janowiak and Arkin*, 1991]	1988–1995	7	1895
Eltahir and Bras [1994a]	1985–1990	6	1950
Vörösmarty et al. [1996]	1979–1984	5	2302
Earth Observer System-Amazon Project	1972–1992	20	2120
NASA GSFC reanalyzed data set	1985–1992	8	2152
NCEP/NCAR reanalyzed data set	1976–1996	20	2322

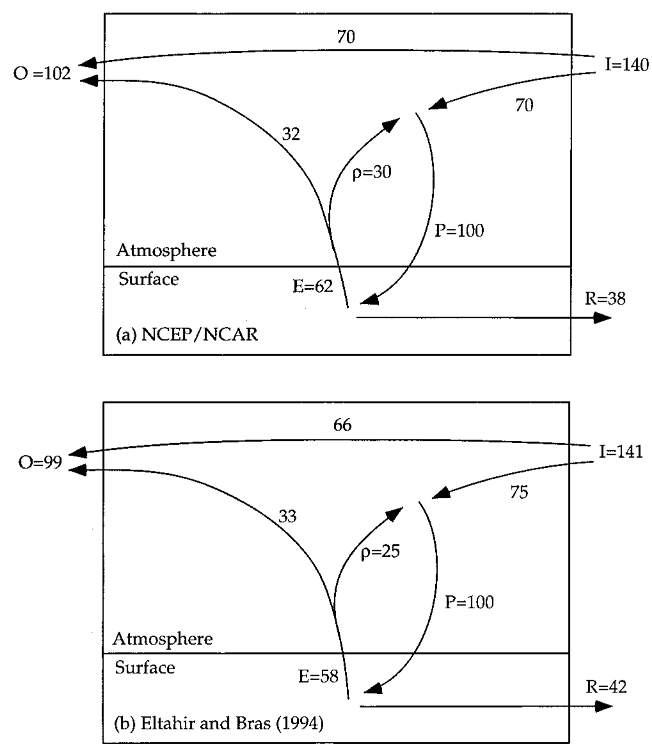

Figure 3. Comparison of the Amazonian hydrologic budget: (a) National Centers for Environmental Protection (NCEP)/National Center for Atmospheric Research (NCAR) reanalyzed data set (this study), $P = 100\% = 2320$ mm yr^{-1}, and (b) European Centre for Medium-Range Weather Forecasts (ECMWF reanalyzed data set [*Eltahir and Bras*, 1994a], $P = 100\% = 1950$ mm yr^{-1}.

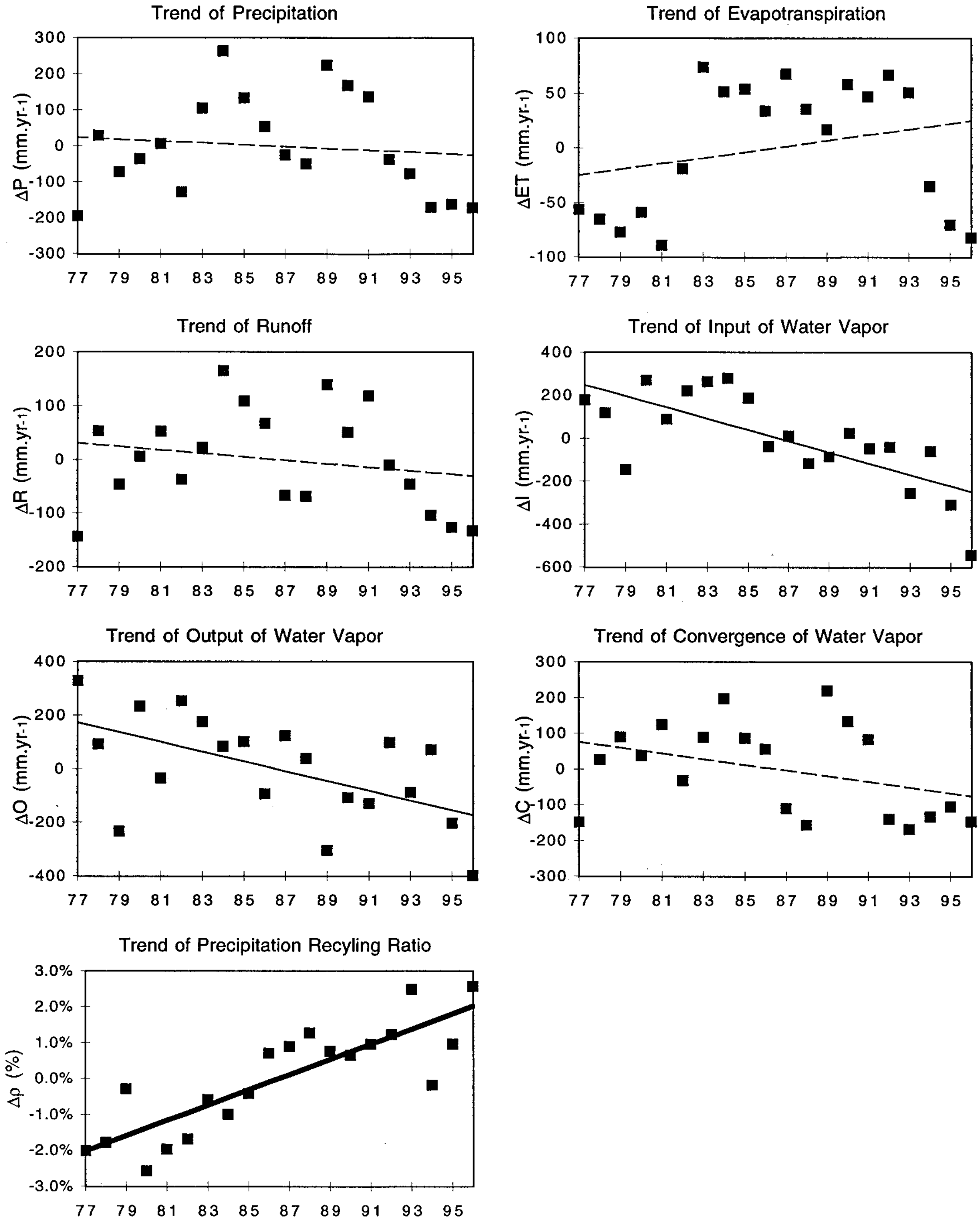

Figure 4. Twenty-year trends in the components of the hydrological cycle in the Amazon basin. Here we plot the annual departures (from the 20-year mean) of each component of the hydrologic cycle plus a linear regression of these departures over time. A dashed line indicates that the trend is not significant at the 5% level; a thin (thick) solid line indicates that the trend is significant at the 1% (0.01%) level according to Mann-Kendall test.

and/or runoff. Comparisons of the NCEP/NCAR evapotranspiration and runoff data with other estimates (Tables 1 and 2) suggested that evapotranspiration (not runoff) was overestimated. On the basis of this observation we apply a correction term to the NCEP/NCAR evapotranspiration estimates, removing the long-term water imbalance (179 mm yr^{-1}). Besides reducing E and making the overall water balance closer to other estimates, the only extra effect of this correction is reducing our estimate of precipitation recycling ratio, which dropped by 2.5% (absolutely) after the correction. Because of this basic correction to the NCEP/NCAR water balance, we conduct the remainder of this study using yearly anomalies so that the difference in the long-term average water balance does not affect the results.

The corrected basin-average water balance (Table 3) shows the average annual atmospheric transport of water vapor into

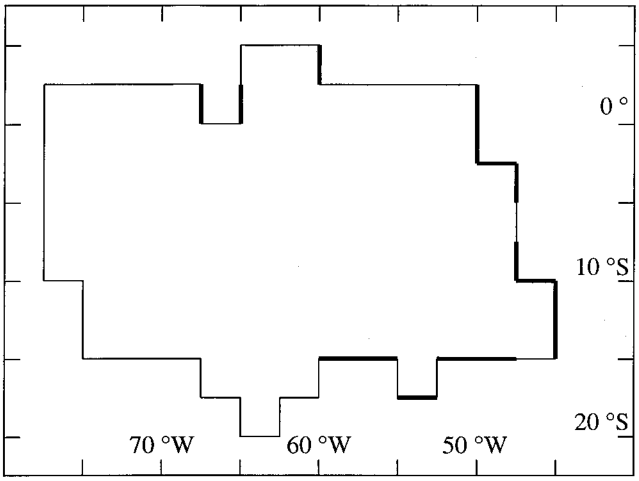

Figure 5. Schematic map of the Amazon basin in a 2.5 × 2.5 grid. The thick lines represent borders where there is a trend in the annual mean water vapor transport significant at the 5% level according to the Mann-Kendall test. See text for details.

(I = 3255 mm yr^{-1}) and out of (O = 2350 mm yr^{-1}) the Amazon basin and the split of precipitation (P = 2322 mm yr^{-1}) between evapotranspiration (1384 mm yr^{-1}, which is ~60% of P) and runoff (937 mm yr^{-1}, which is ~40% of P). These values are comparable to other estimates of the Amazon basin's hydrologic budget (Table 4 and Figure 3; see also Table 4 by *Matsuyama* [1992]).

Table 5. Matrix of Correlations

	ΔP	ΔE	ΔR	ΔI	ΔO	ΔC	$\Delta \rho$
ΔP	1.00						
ΔE	0.58	1.00					
ΔR	0.94	0.44	1.00				
ΔI	0.41	0.22	0.47	1.00			
ΔO	−0.11	0.16	−0.05	0.81	1.00		
ΔC	0.84	0.13	0.86	0.46	−0.16	1.00	
$\Delta \rho$	−0.04	0.38	−0.19	−0.81	−0.66	−0.36	1.00

Considering the entire land-atmosphere water budget, mass conservation implies that the long-term average convergence of water vapor transport in the basin (C = 905 mm yr^{-1}) should be matched by runoff of water out of the basin (R = 937 mm yr^{-1}). However, in the NCEP/NCAR data a small difference (32 mm yr^{-1}) remains unaccounted for. This error in the land-atmosphere water budget is ~3.5% of the net water vapor convergence (or <0.7% of the total water vapor input to the atmosphere, $I + E$) and may be a consequence of the assumption (in the NCEP/NCAR data set) that there is no water vapor above 300 hPa [*Kalnay et al.*, 1996].

Our estimate of the precipitation recycling ratio ρ is 30%, which is similar to the 25% value found by *Eltahir and Bras* [1994a]. Some of the older estimates of precipitation recycling, which do not assume well-mixed water vapor, place ρ between 48% and 52% [*Molion*, 1975; *Marques et al.*, 1977].

Typically in the literature, the atmospheric water vapor transport is integrated above 1000 hPa, instead of the surface

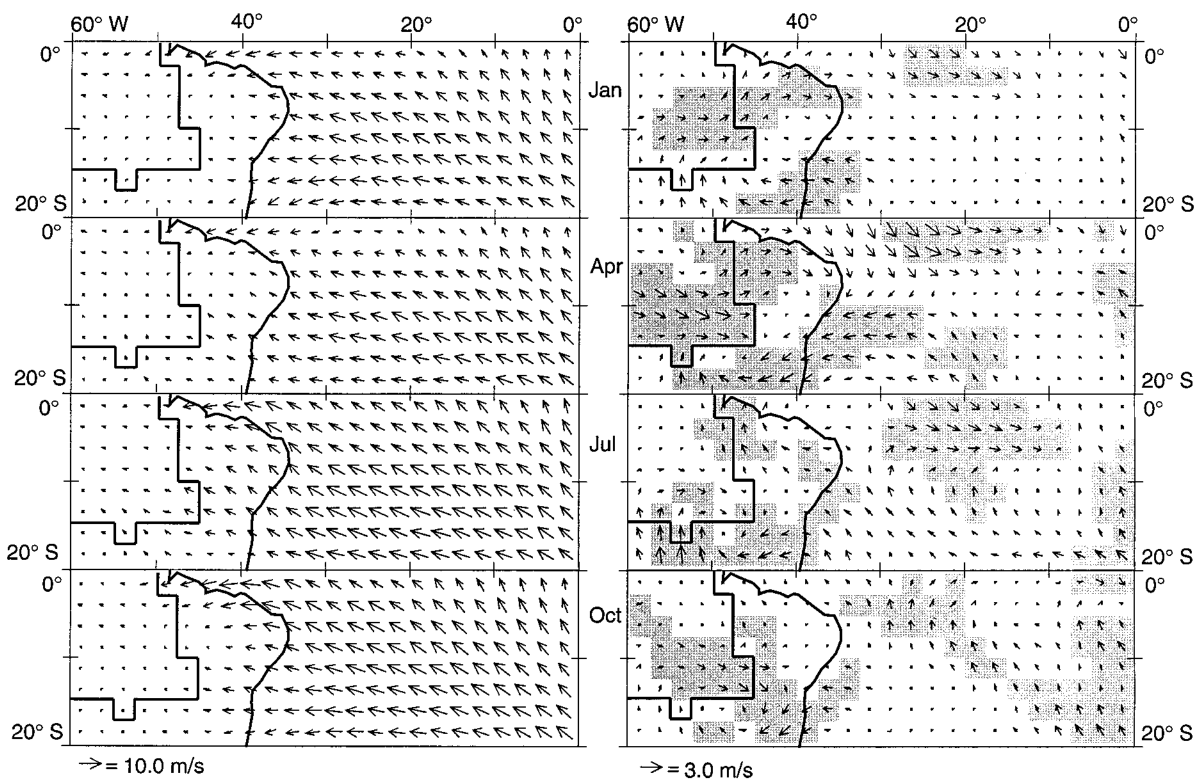

Figure 6. Mean 1976–1996 circulation patterns at 1000 hPa and trends in the circulation for the months of January, April, July, and October. Trends in the atmospheric circulation are depicted as changes in wind vectors over the 20-year record, as calculated by the end-points of a linear regression of the entire record of wind data. Shaded areas indicate where the trend is significant at the 5% level.

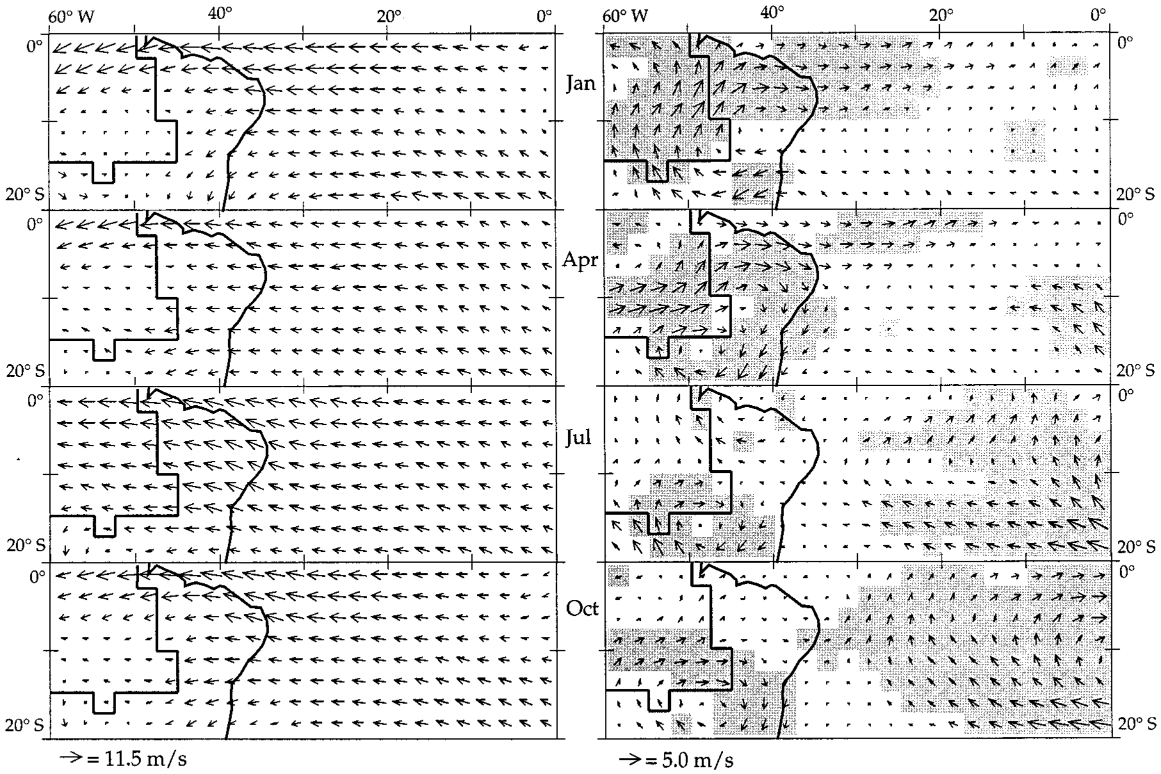

Figure 7. As in Figure 6, but for 850 hPa.

pressure, as we did in this study (equation (1)). In regions that have high-altitude borders, such as the Andes in the Amazon basin, this methodology can introduce biases, underestimating the water vapor convergence. For example, *Rao et al.* [1996], using 5 years of European Centre for Medium-Range Weather Forecasts (ECMWF) data, calculated a convergence to the Amazon basin around 1.5×10^{-5} kg H_2O m^{-2} s^{-1} (equivalent to 473 mm yr^{-1}), which is much smaller than our estimate (905 mm yr^{-1}). Also, *Matsuyama* [1992], who also used ECMWF data for the First Global Atmospheric Research Program (GARP) Global Experiment (FGGE) period, had to multiply the water vapor convergence by 1.37 to match the observed runoff of the basin.

5. 20-Year Trends

In order to evaluate the 20-year trends in the hydrologic budget of the Amazon basin we examine the time series of each of the components of the annual budget (Figure 4). For each we use the Mann-Kendall statistical test to determine the direction and significance of trends. According to our analysis, there is no significant (at the 5% level) 20-year trend in basin-average precipitation, evapotranspiration, runoff, or water vapor flux convergence.

However, there are decreasing trends in water vapor input and output (significant at 1% level) and an increasing trend in precipitation recycling (significant at the 0.01% level). Inspecting the hydrological budget terms at each grid cell, we find that the trends in annual mean atmospheric water vapor transport are occurring in the eastern part of the basin, where water vapor is advected in from the tropical South Atlantic (Figure 5). In the NCEP/NCAR data set, of the total input of water vapor to the Amazon basin, 64% enters through the eastern border, while 34% enters through the northern border of the basin. No trend was found in the annual mean meridional inflow through the northern border of the basin, although significant increasing trends were found in some months. Since this study concentrates on annual mean fluxes we focused our analysis in the eastern border.

Upon further examination we find that there are strong correlations between the interannual variations in water vapor input (I) and output (O) and between the interannual variations in precipitation recycling (ρ) and water vapor input (I) (Table 5). As a result, we believe that external factors are causing the decrease in the water vapor input; the decreasing trend in the water vapor output and the increasing trend in the precipitation recycling are a consequence of the trend in the input (as implicit in equation (2)).

We repeated this analysis with the NASA GSFC DAO reanalyzed meteorological data set. Although the DAO data set covers a shorter period (1985–1993), the same general features emerge from the analysis. Again, there are decreasing trends in water vapor input and water vapor output, increasing rates of precipitation recycling, and nearly steady rates of precipitation and evapotranspiration.

6. Discussion

The decreasing trend in the atmospheric transport of water vapor into the basin could be a result of several processes occurring near the eastern border of the basin: (1) a decrease in the mean flow in from the ocean, (2) a decrease in the total precipitable water (vertically integrated water vapor content) in the region, or at least in some borders, (3) a decrease in the eddy flow, or (4) some combination of the three. In order to isolate which mechanism is responsible for the trend we break

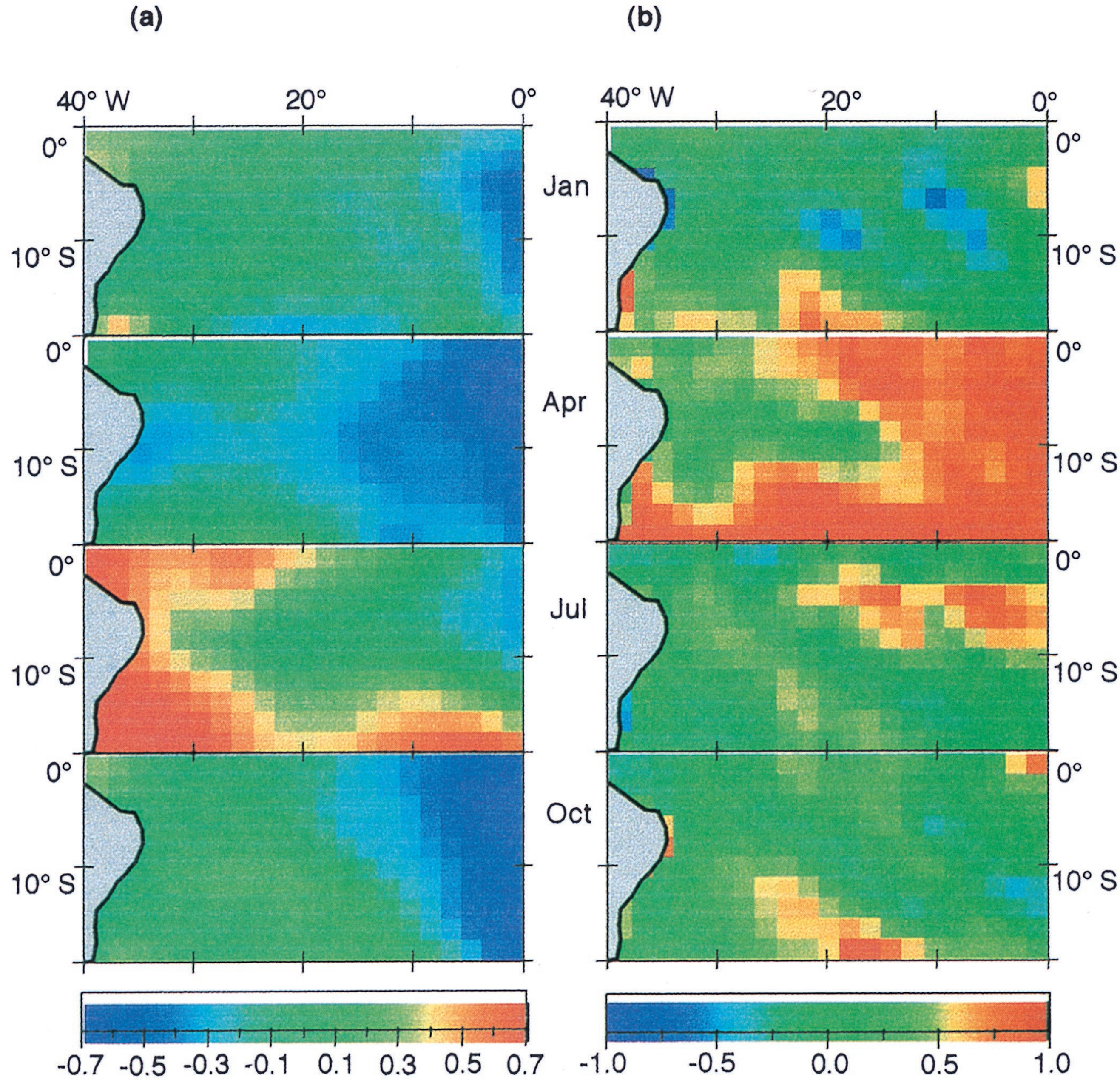

Plate 1. Trends in the (a) sea level pressure (SLP) and (b) sea surface temperature (SST), for the months of January, April, July, and October. Trends in SLP (SST) are depicted as changes in pressure (temperature) over the 20-year record as calculated by the end-points of a linear regression of the entire record of atmospheric pressure (SST) data.

apart the transport equation (1) and consider each term separately. We find that the trend in water vapor input is a consequence of a decrease in the transport by the mean flow. There are no significant trends in precipitable water, except for southeastern Amazonia in the months of June (when there is a decreasing trend) and December (when there is an increasing trend). Also, there is no significant trend in the transport by the eddy flow. Physically, this represents a decrease in the strength of the southeasterly trade winds, which is a major source of water vapor into the basin.

Decreases in the strength of the trade winds along the eastern border of the Amazon basin is not a localized phenomenon but rather a large-scale one, extending for 1000 km or more into the South Atlantic. We analyze the wind patterns over the South Atlantic at 1000 and over the continent at 850 hPa in the NCEP/NCAR data set to characterize the 20-year average circulation patterns and any significant circulation changes (Figures 6 and 7). Twenty-year trends in the atmospheric circulation (Figures 6b and 7b) are depicted as changes in wind vectors, as calculated by the end-points of a linear regression of 20-year wind data. Along the eastern border of the basin we see that the easterly winds are significantly weakened and, in some cases, reverse direction.

Using surface wind observations from the Comprehensive Ocean-Atmosphere Data Set (COADS) data set, *Wagner* [1996] also noted that the strength of the southeasterly (north-easterly) trade winds in the Atlantic sector decreased (increased) between 1951 and 1990, which is consistent with our results. *Wagner* [1996] also mentions trends in the atmospheric transport of water vapor, but his results are not comparable to ours because he did not calculate the three-dimensional water vapor budget.

Over this 20-year record of the NCEP/NCAR data set we also find that sea level pressure is increasing (decreasing) over the western (eastern) tropical South Atlantic (Plate 1). This causes a weakening of the east-to-west pressure gradient over the tropical South Atlantic sector, which agrees with the changing wind patterns.

Changes in wind speed have an important role on the sea surface temperatures in this region through the evaporative cooling of the ocean surface [*Curtis and Hastenrath*, 1995]. In the NCEP/NCAR data we see that the general reduction of surface wind speeds is associated with a significant warming of sea surface temperatures in the tropical South Atlantic (Figure 8b). This warming trend has also been well documented by surface observations [*Hastenrath*, 1990; *Parker and Folland*, 1991; *Hastenrath and Wolter*, 1992; *Cane et al*., 1997; *Latif et al*., 1997; *Venegas et al*., 1997].

Although some atmospheric general circulation model (AGCM) experiments of Amazonian deforestation suggest that the South Atlantic temperatures would rise after a complete deforestation of the basin [*Zeng et al*., 1996; *Sud et al*., 1996], it is not clear that this warming is associated with the on-going Amazonian deforestation. For example, an empirical orthogonal function (EOF) analysis of the tropical Atlantic sea surface temperatures (SSTs) [*Parker and Folland*, 1991, Figure 7] shows a 60-year trend in the SST dipole pattern (i.e., warming in the south equatorial Atlantic, cooling in the north equatorial Atlantic), while intense deforestation in Amazonia has been a relatively recent phenomenon.

7. Conclusions

This analysis suggests that there has been a decrease in the main source of water vapor into the Amazon basin. This change in the water vapor budget is associated with large-scale changes in the general circulation of the tropical atmosphere. While the annual mean flow of water vapor into the basin has decreased over these 20 years, the flow of water vapor out of the basin has also decreased, with no statistically significant change in the net water vapor convergence. In addition, the proportion of the basin's water vapor contributed through local evapotranspiration (i.e., the recycling ratio) has significantly increased, and no significant trends have been noticed in terms of the basin-average precipitation and runoff.

This result raises another issue: scenarios of increased deforestation [*Dickinson and Henderson-Sellers*, 1988; *Lean and Warrilow*, 1989; *Shukla et al*., 1990; *Nobre et al*., 1991; *Dickinson and Kennedy*, 1992; *Henderson-Sellers et al*., 1993; *Lean and Rowntree*, 1993; *Diermayer and Shukla*, 1994; *Eltahir and Bras*, 1994b; *Polcher and Laval*, 1994; *Walker et al*., 1995; *Gash et al*., 1996; *Sud et al*., 1996; *Zeng et al*., 1996; *Lean and Rowntree*, 1997] and of increasing CO_2 concentrations (related to the physiological effects on canopy transpiration) [*Friend and Cox*, 1995; *Henderson-Sellers et al*., 1995; *Pollard and Thompson*, 1995; *Sellers et al*., 1996; *Costa and Foley*, 1997] both exhibit large decreases in Amazonian evapotranspiration. If changes in water vapor transport were to continue, combined with these anticipated decreases in evapotranspiration, all of the sources of water vapor into the Amazonian atmosphere would be significantly altered. Future studies will need to examine how precipitation patterns and freshwater resources within the basin would respond to such conditions.

Acknowledgments. The NCEP/NCAR reanalysis data set was provided through the NOAA Climate Diagnostics Center (http://www.cdc.noaa.gov/). The EOS-Amazon precipitation data set was provided through the Oak Ridge National Laboratory Distributed Active Archive Center (http://www-eosdis.ornl.gov/hydrology/guides/eosram_project.html). The DAO reanalysis data set was provided through the NASA GSFC Data Assimilation Office (http://dao.gsfc.nasa.gov/). M. H. Costa is supported through a Brazilian CAPES fellowship. This research is also supported by the National Science Foundation through grant ATM-9506588 and the Climate, People and Environment Program (CPEP) of the Institute of Environmental Studies, University of Wisconsin. We thank J. Lenters, N. Ramankutty, S. Curtis, M. Coe, J. Kutzbach, and two anonymous reviewers for their comments.

References

Cane, M. A., A. C. Clement, A. Kaplan, Y. Kushnir, D. Pozdnyakov, R. Seager, S. E. Zebiak, and R. Murtugudde, Twentieth-century sea surface temperature trends, *Science*, *275*, 957–960, 1997.

Chu, P.-S., Z. P. Yu, and S. Hastenrath, Detecting climate change concurrent with deforestation in the Amazon basin: Which way has it gone? *Bull. Am. Meteorol. Soc*., *75*, 579–583, 1994.

Costa, M. H., and J. A. Foley, The water balance of the Amazon basin: Dependence on vegetation cover and canopy conductance, *J. Geophys. Res*., *102*, 23,973–23,990, 1997.

Costa, M. H., and J. A. Foley, A comparison of precipitation data sets for the Amazon basin, *Geophys. Res. Lett*., *25*, 155–158, 1998.

Curtis, W. R. S., III, Circulation mechanisms of climatic variability in the tropics, Ph.D. Thesis, Madison, Univ. of Wis., 1998.

Curtis, S., and S. Hastenrath, Forcing of anomalous sea surface temperature evolution in the tropical Atlantic during Pacific warm events, *J. Geophys. Res*., *100*, 15,835–15,847, 1995.

Dickinson, R. E., and A. Henderson-Sellers, Modelling tropical deforestation: A study of GCM land-surface parameterizations, *Quart. J. R. Meteorol. Soc*., *Ser. B*, *114*, 439–462, 1988.

Dickinson, R. E., and P. Kennedy, Impacts on regional climate of amazon deforestation, *Geophys. Res. Lett*., *19*, 1947–1950, 1992.

Diermayer, P. A., and J. Shukla, Albedo as a modulator of climate response to tropical deforestation, *J. Geophys. Res*., *99*, 20,863–20,877, 1994.

Eltahir, E. A. B., and R. L. Bras, Precipitation recycling in the Amazon basin, *Quart. J. R. Meteorol. Soc*., *120*, 861–880, 1994a.

Eltahir, E. A. B., and R. L. Bras, Sensitivity of regional climate to deforestation in the Amazon basin, *Adv. Water Res*., *17*, 101–115, 1994b.

Friend, A. D., and P. M. Cox, Modelling the effects of atmospheric CO_2 on vegetation-atmosphere interactions, *Agricultural For. Meteorol*., *73*, 285–295, 1995.

Gash, J. H. C., C. A. Nobre, J. M. Roberts, and R. L. Victoria, *Amazonian Deforestation and Climate*, 1st ed., 611 pp., John Wiley, New York, 1996.

Gentry, A. H., and J. Lopez-Parody, Deforestation and increased flooding in the upper-Amazon, *Science*, *210*, 1354–1356, 1980.

Harris, R. C., et al., The Amazon Boundary Layer experiment (ABLE 2A) dry season 1985, *J. Geophys. Res*., *93*, 1351–1360, 1988.

Hastenrath, S., Decadal-scale changes of the circulation in the tropical Atlantic sector associated with Sahel drought, *Int. J. Climatol*., *10*, 459–472, 1990.

Hastenrath, S., and K. Wolter, Large-scale patterns and long-term trends of circulation variability associated with Sahel rainfall anomalies, *J. Meteorol. Soc. Jpn*., *70*, 1045–1055, 1992.

Henderson-Sellers, A., R. E. Dickinson, T. B. Durbidge, P. J. Kennedy, K. McGuffie, and A. J. Pitman, Tropical deforestation: Modeling local- to regional-scale climate change, *J. Geophys. Res*., *98*, 7289–7315, 1993.

Henderson-Sellers, A., K. McGuffie, and C. Gross, Sensitivity of global climate model simulations to increased stomatal resistance and CO_2 increases, *J. Clim*., *8*, 1738–1756, 1995.

Janowiak, E. E., and P. A. Arkin, Rainfall variation in the tropics during 1986–1989, as estimated from observations of cloud-top temperature, *J. Geophys. Res.*, *96*, 3359–3373, 1991.
Kalnay, E., et al., The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471, 1996.
Korzun, V. I. (Ed.), *World Water Balance and Water Resources of the Earth*, UNESCO, Paris, 1978.
Kousky, V. E., M. T. Kayano, and I. F. A. Cavalcanti, A review of the southern oscillation: Oceanic, atmospheric circulation changes and related rainfall anomalies, *Tellus*, *Ser. A*, *36*, 490–504, 1984.
Latif, M., R. Kleeman, and C. Eckert, Greenhouse warming, decadal variability, or El Niño? An attempt to understand the anomalous 1990s, *J. Clim.*, *10*, 2221–2239, 1997.
Lean, J., and P. R. Rowntree, A GCM simulation of the impact of Amazonian deforestation on climate using an improved canopy representation, *Quart. J. R. Meteorol. Soc.*, *119*, 509–530, 1993.
Lean, J., and P. R. Rowntree, Understanding the sensitivity of a GCM simulation of Amazonian deforestation to the specification of vegetation and soil characteristics, *J. Clim.*, *10*, 1216–1235, 1997.
Lean, J., and D. A. Warrilow, Simulation of the regional climatic impact of Amazon deforestation, *Nature*, *342*, 411–413, 1989.
Leemans, R., and W. P. Cramer, The IIASA database for mean monthly values of temperature, precipitation and cloudiness on a global terrestrial grid, *Work. Pap. WP-90-41*, Int. Inst. for Appl. Syst. Anal., Laxenburg, Austria, 1990.
Legates, D. R., and C. J. Willmott, Mean seasonal and spatial variability in gauge-corrected, global precipitation, *Int. J. Climatol.*, *10*, 111–127, 1990.
Lettenmaier, D. P., E. F. Wood, and J. R. Wallis, Hydro-climatological trends in the continental United States, 1948–88, *J. Clim.*, *7*, 586–607, 1994.
Marengo, J. A., Interannual variability of surface climate in the Amazon basin, *Int. J. Climatol.*, *12*, 853–863, 1992.
Marengo, J. A., Variations and change in South American streamflow, *Clim. Change*, *31*, 99–117, 1995.
Marengo, J. A., and S. Hastenrath, Case studies of extreme climatic events in the Amazon basin, *J. Clim.*, *6*, 617–627, 1993.
Marengo, J. A., J. Tomasella, and C. R. Uvo, Trends in streamflow and rainfall in tropical South America: Amazonia, eastern Brazil, and northwestern Peru, *J. Geophys. Res.*, *103*, 1775–1783, 1998.
Marques, J., J. M. Santos, N. A. Villa Nova, and E. Salati, Precipitable water and water vapor flux between Belém and Manaus, *Acta Amazônica*, *7*, 355–362, 1977.
Marques, J., E. Salati, and J. M. Santos, Cálculo da evapotranspiração real na bacia amazônica através do método aerológico, *Acta Amazônica*, *10*, 357–361, 1980.
Matsuyama, H., The water budget in the Amazon River basin during the FGGE period, *J. Meteorol. Soc. Jpn.*, *70*, 1071–1083, 1992.
Milliman, J., and R. Meade, World-wide delivery of river sediment to the oceans, *J. Geol.*, *91*, 1–21, 1983.
Mintz, Y., and Y. V. Serafini, A global monthly climatology of soil moisture and water balance, *Clim. Dyn.*, *8*, 13–27, 1992.
Molion, L. C. B., A climatonomic study of the energy and moisture fluxes of the Amazon's basin with considerations of deforestation effects, Ph.D. thesis, Univ. of Wis., Madison, 1975.
Molion, L. C. B., Climate variability and its effects on Amazonian hydrology, *Interciência*, *15*, 367–372, 1990.
Neves, E. K., A estação chuvosa na Amazônia, de 1988 a 1989, e sua relação com a circulação geral da atmosfera, M. S. thesis, Univ. Federal de Viçosa, Viçosa, Brazil, 1995.
Nobre, C. A., P. J. Sellers, and J. Shukla, Amazonian deforestation and regional climate change, *J. Clim.*, *4*, 957–988, 1991.
Oki, T., K. Musiake, H. Matsuyama, and K. Masuda, Global atmospheric water balance and runoff from large river basins, *Hydrol. Proc.*, *9*, 655–678, 1995.
Paiva, E. M. C. D., and R. T. Clarke, Time trends in rainfall records in Amazonia, *Bull. Am. Meteorol. Soc.*, *76*, 2203–2209, 1995.
Parker, D. E., and C. K. Folland, Worldwide surface temperature trends since the mid-19th century, in *Greenhouse-Gas-Indiced Climatic Change: A Critical Apraisal of Simulations and Observations*, edited by M. E. Schlesinger, pp. 173–193, Elsevier, New York, 1991.
Peixoto, J. P., and A. H. Oort, *Physics of Climate*, 520 pp., Am. Inst. of Phys., New York, 1993.
Polcher, J., and K. Laval, The impact of African and Amazonian deforestation on tropical climate, *J. Hydrol.*, *155*, 389–405, 1994.
Pollard, D., and S. L. Thompson, The effect of doubling stomatal resistance in a global climate model, *Global Planet. Change*, *10*, 129–161, 1995.
Rao, V. B., I. F. A. Cavalcanti, and K. Hada, Annual variation of rainfall over Brazil and water vapor characteristics over South America, *J. Geophys. Res.*, *101*, 26,539–26,551, 1996.
Richey, J. E., C. A. Nobre, and C. Deser, Amazon River discharge and climate variability: 1903 to 1985, *Science*, *246*, 101–103, 1989.
Roads, J. O., S.-C. Chen, M. Kanamitsu, and H. Juang, Surface water characteristics in the NCEP global spectral model and reanalysis, *J. Geophys. Res.*, in press, 1999.
Rocha, H. R., C. A. Nobre, and M. C. Barros, Variabilidade natural de longo prazo no ciclo hidrológico da Amazônia, *Climanálise*, *4*, 36–43, 1989.
Russell, G. L., and J. R. Miller, Global river runoff calculated from a global atmospheric general circulation model, *J. Hydrol.*, *117*, 241–254, 1990.
Schubert, S. D., J. Pfaendtner, and R. Rood, An assimilated data set for Earth sciences applications, *Bull. Am. Meteorol. Soc.*, *74*, 2331–2342, 1993.
Sellers, P. J., et al., Comparison of radiative and physiological effects of doubled atmospheric CO_2 on climate, *Science*, *271*, 1402–1406, 1996.
Shukla, J., C. Nobre, and P. Sellers, Amazon deforestation and climate change, *Science*, *247*, 1322–1325, 1990.
Sud, Y. C., G. K. Walker, J.-H. Kim, G. E. Liston, P. J. Sellers, and W. K.-M. Lau, Biogeophysical consequences of a tropical deforestation scenario: A GCM simulation study, *J. Clim.*, *9*, 3225–3247, 1996.
UNESCO, World water balance and water resources of the Earth, 663 pp., U. N. Educat. Sci. Cult. Org., Paris, France, 1978.
Venegas, S. A., L. A. Mysak, and D. N. Straub, Atmosphere-ocean coupled variability in the South Atlantic, *J. Clim.*, *10*, 2904–2920, 1997.
Villa Nova, N. A., E. Salati, and E. Matsui, Estimativa da evapotranspiração na bacia Amazônica, *Acta Amazonica*, *6*, 215–228, 1976.
Vörösmarty, C. J., B. Moore III, A. L. Grace, and M. P. Gildea, Continental scale models of water balance and fluvial transport: An application to South America, *Global Biogeochem. Cycles*, *3*, 241–265, 1989.
Vörösmarty, C. J., C. J. Willmott, B. J. Choudhury, A. L. Schloss, T. K. Stearns, S. M. Robeson, and T. J. Dorman, Analysing the discharge regime of a large tropical river through remote sensing, ground-based climatic data, and modeling, *Water Resour. Res.*, *32*, 3137–3150, 1996.
Wagner, R. G., Decadal-scale trends in mechanisms controlling meridional sea surface temperature gradients in the tropical Atlantic, *J. Geophys. Res.*, *101*, 16,683–16,694, 1996.
Walker, G. K., Y. C. Sud, and R. Atlas, Impact of the ongoing Amazonian deforestation on local precipitation: A GCM simulation study, *Bull. Am. Meteorol. Soc.*, *76*, 346–361, 1995.
Willmott, C. J., C. Rowe, and Y. Mintz, Climatology of the terrestrial seasonal cycle, *J. Climatol.*, *5*, 589–606, 1985.
Zeng, N., R. E. Dickinson, and X. Zeng, Climatic impact of Amazon deforestation: A mechanistic model study, *J. Clim.*, *9*, 859–883, 1996.

M. H. Costa, Departamento de Engenharia Agrícola, Universidade Federal de Viçosa, 36571-000 Viçosa, Brazil.

J. A. Foley, Climate, People and Environment Program CPEP, Institute for Environmental Studies, Department of Atmospheric and Oceanic Sciences, University of Wisconsin, 1225 W. Dayton Street, Madison, WI 53706. (jfoley@facstaff.wisc.edu)

(Received January 28, 1998; revised November 30, 1998; accepted December 9, 1998.)