

NOTES AND CORRESPONDENCE

Feedbacks between Hydrological Processes in Tropical South America and Large-Scale Ocean–Atmospheric Phenomena

GERMÁN POVEDA AND OSCAR J. MESA

Postgrado en Aprovechamiento de Recursos Hidráulicos, Facultad de Minas, Universidad Nacional de Colombia, Medellín, Colombia

11 December 1995 and 6 September 1996

ABSTRACT

The hydroclimatology of tropical South America is strongly coupled to low-frequency large-scale oceanic and atmospheric phenomena occurring over the Pacific and the Atlantic Oceans. In particular, El Niño–Southern Oscillation (ENSO) affects climatic and hydrologic conditions on timescales ranging from seasons to decades. With some regional differences in timing and amplitude, tropical South America exhibits negative rainfall and streamflow anomalies in association with the low–warm phase of the Southern Oscillation (El Niño), and positive anomalies with the high–cold phase. Such dependence is illustrated in the hydroclimatology of Colombia through several empirical analyses: correlation, empirical orthogonal functions, principal component, and spectral analysis, and discussion of the major physical mechanisms. Observations show that ENSO's effect on river discharges occurs progressively later for rivers toward the east in Colombia and northern South America. Also, the impacts of La Niña are more pronounced than those of El Niño. Evidence is also presented to show that processes arising from land–atmosphere interactions in tropical South America affect sea surface temperatures in the Caribbean and the north tropical Atlantic. A hypothesis is formulated to explain these feedback mechanisms through perturbations in precipitation, soil moisture, and evapotranspiration over the continent. To begin with, the occurrence of both phases of ENSO affects all those fields. The proposed mechanisms would constitute the “land–atmosphere” bridge connecting Pacific and Atlantic SST anomalies.

1. Introduction

The annual distribution of rainfall over tropical South America is primarily influenced by the position of the intertropical convergence zone (ITCZ). The main controls of the rain space distribution are the presence of the Andes mountains and the eastern Pacific, and western Atlantic Oceans, the atmospheric circulation over the Amazon basin, and vegetation and soil moisture contrasts. Large quantities of precipitation, evapotranspiration, soil moisture, and runoff are present in tropical South America, as compared with world averages. The region is a major center of convective activity, mostly developed within large cumulonimbus clouds, from which latent heat is continuously released into the atmosphere thus influencing the Hadley cells and overall global circulation (Riehl and Malkus 1958). The excess of precipitation over evapotranspiration in the region is such that the combined runoffs of the Amazon, Orinoco, and Magdalena rivers account for 18.3% of the total inflow to the world oceans (Baumgartner and Reichel 1975, 95). The Atrato River in Colombia drains 35 702

km² of the wettest areas of the planet, producing a mean annual discharge of 4557 m³ s⁻¹ and an equivalent runoff of 127.6 L s⁻¹ km⁻², 5–6 times larger than the Amazon. The origin of this highly wet region over northwestern South America lies in the low-level westerly flow from the Pacific Ocean over inland Colombia. These winds are colder and moister than the dominant easterly trades from the Atlantic and the Caribbean (López and Howell 1967). The confluence of the two winds, combined with the effects of surface warming and orographic lifting, produces a highly unstable atmospheric profile causing strong convection and heavy precipitation along the Pacific coast and western flanks of the Cordillera Occidental. This region is favored for development of tropical mesoscale convective complexes (Velasco and Fritsch 1987).

On interannual timescales, low-frequency large-scale ocean–atmosphere phenomena are highly coupled to the hydroclimatology of the region. In particular, El Niño–Southern Oscillation (ENSO) is a major forcing mechanism of climatic and hydrological anomalies. The physics of ENSO and its climatic consequences can be found in Horel and Wallace (1981), van Loon and Madden (1981), Rasmusson and Carpenter (1982), Glantz et al. (1991), Ropelewski and Halpert (1987), Rasmusson (1991), Trenberth (1991), and Diaz and Markgraff (1992).

The purpose of this paper is twofold: 1) to study the

Corresponding author address: Dr. Germán Poveda, Facultad de Minas, Universidad Nacional de Colombia, 1027 A. A. Medellín, Colombia.
E-mail: gpoveda@perseus.unalmed.edu.co

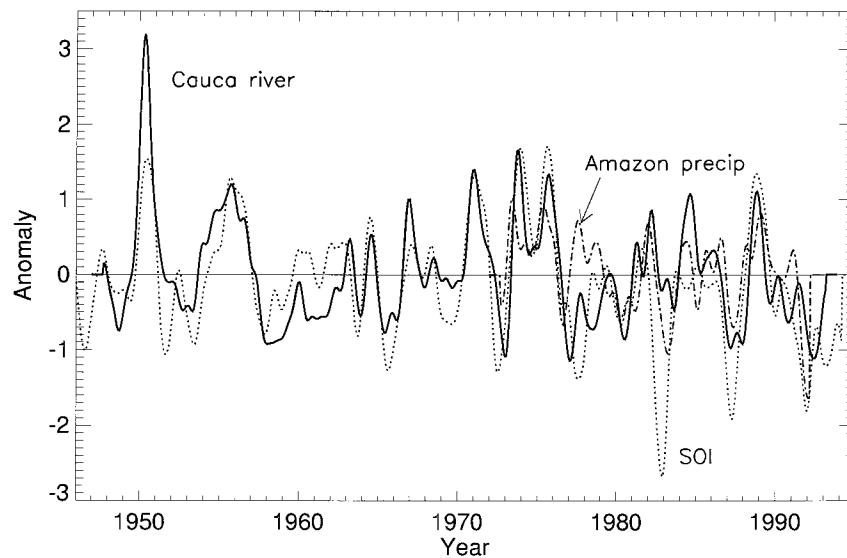


FIG. 1. Time evolution of the SOI (dotted line), the monthly discharges of the Cauca River, Salvajina, Colombia (solid thick line), and average precipitation in the Amazon River basin. Data have been low-pass (12-month) filtered.

interannual variability of hydrologic anomalies of rainfall and river discharges in tropical South America, particularly Colombia and the Amazon River basin, and to identify their relationship with ENSO, and 2) to present evidence suggesting that hydrological processes in the region can influence oceanic-atmospheric interactions in the Caribbean and northern tropical Atlantic. We hypothesize a model to explain the nature of this feedback with the support of independent observations. In conclusion, the implications of long-term oscillations, such as ENSO, for regional hydroclimatology and water resources planning, are discussed.

2. Empirical analyses

Overall, there is a coherent pattern of hydrological anomalies in tropical South America during extreme phases of ENSO. This is clear in regions of Costa Rica (Waylen et al. 1996); Panama (Estoque et al. 1985); Colombia (Poveda and Mesa 1993; Poveda 1994; Poveda and Mesa 1995), Venezuela (Pulwarty et al. 1992), some regions of Ecuador (Gessler 1995), Amazon basin rainfalls and discharges (Vörösmarty et al. 1996; Kousky and Kayano 1994; Marengo and Hastenrath 1993; Marengo 1992; Obregón and Nobre 1990; Richey et al. 1989; Lau and Sheu 1988), and other regions of Brazil (Kousky et al. 1984; Rao and Hada 1990; Hastenrath and Greischar 1993; Kayano et al. 1988; Chu 1991). Aceituno (1988, 1989), Rogers (1988), Kiladis and Diaz (1989), Hastenrath (1976, 1990), and Halpert and Ropelewski (1992) place this region in a broader hemispherical and global context. Generally, negative anomalies in rainfall and streamflows are associated with the warm phase of ENSO (El Niño), and positive anomalies with the cold phase (La Niña), although there are some

regional differences in timing and amplitude. As an illustration, Fig. 1 shows smoothed monthly values of the Southern Oscillation index (SOI, defined as the standardized difference between Tahiti and Darwin sea level pressures), the discharges of the Cauca River, Colombia (1946–94), and the average rainfall over Amazon basin ($5.965 \times 10^6 \text{ km}^2$). The latter data are estimated from the set produced by the Earth Observing System Amazon Project (Instituto Nacional de Pesquisas Espaciais, Brazil, and the University of Washington, and provided by the Global Hydrology and Climate Center of the National Aeronautics and Space Administration), which contains monthly rainfall gridded ($0.2^\circ \text{ lat} \times 0.2^\circ \text{ long}$) during the period 1972–92. A 12-month low-pass digital filter is applied to remove higher frequencies associated with annual and intraannual variability. The derived correlation coefficient between SOI and the Amazon rainfall is 0.63, statistically significant at the 99.99% level once the degrees of freedom are reduced according to the scale of fluctuation of the processes (Vanmarcke 1988; Mesa and Poveda 1993).

To illustrate the effect of extreme phases of ENSO on Colombian hydrology, Fig. 2 (top) presents the monthly discharges of the Magdalena river at Puerto Berrío, during El Niño (triangles) and La Niña (squares) years, according to the classification given by Kiladis and Diaz (1989). The hydrologic year is considered from June (year 0) through May (year +1). Figure 2 (bottom) illustrates the ratio of monthly mean discharges for the whole record and those in extreme phases of ENSO.

a. Correlation analysis

Correlation analyses are calculated between seven climatic variables over the Pacific and rainfall in Colom-

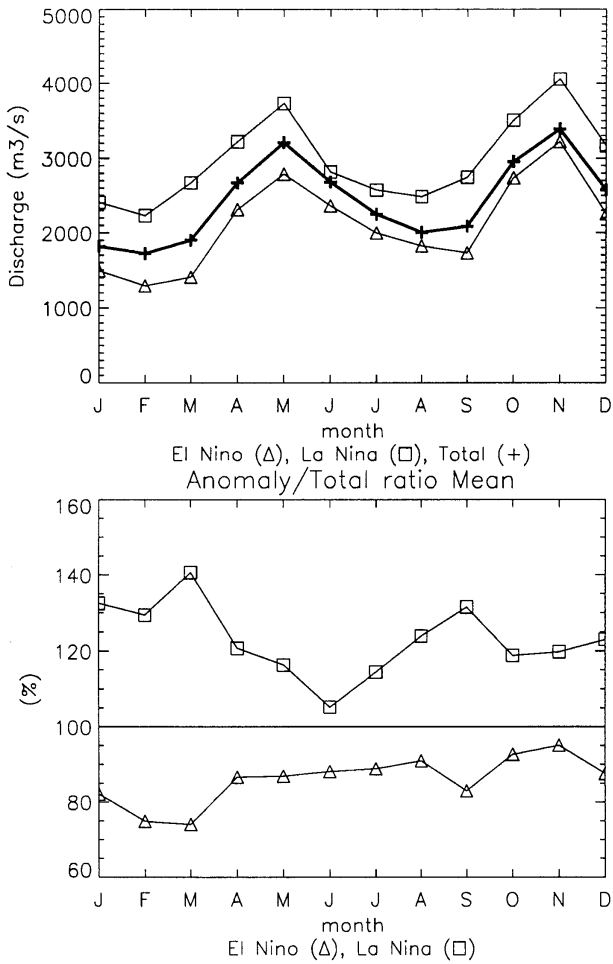


FIG. 2. Monthly anomalies of the Magdalena River at Puerto Berrío, Colombia, with respect to the multiannual mean for El Niño (triangles) and La Niña (squares) years (top). Ratio of the average monthly discharges for El Niño (triangles) and La Niña (squares) to the multiannual averages (bottom).

bia. The variables used are the following: Southern Oscillation index (SOI), monthly mean sea surface temperature (SST) at regions Niño-1-2 (0°-10°S, 90°-80°W), Niño-3 (5°N-5°S, 150°-90°W), and Niño-4 (5°N-5°S, 160°E-150°W), and monthly mean zonal wind velocity in those regions (Uwin). All are extracted from the Comprehensive Ocean-Atmosphere Data Set (COADS; Slutz et al. 1985). The series are first smoothed by using 12-month running means to facilitate the examination of correlations at interannual timescales. To ease interpretation of the results (Table 1) the signs of the SSTs and some zonal wind indices are inverted. All coefficients are significant at the 95% level and show that Colombian precipitation is most highly correlated with the SOI, wind velocity at Niño-4, and SST at Niño-4 (N4), Niño-3 (N3), and Niño-1-2 (N1). Interestingly, the Niño-4 region in the central Pacific returns higher correlations than other regions closer to South America. Results (not shown here) suggest that

additional variables such as the specific humidity in the Niño-1-2 region, and the meridional gradient of SST between the Colombian and Peruvian coasts are also correlated to precipitation variability over western and central Colombia.

Cross-correlation analyses between the SOI and discharges suggest that the influence of ENSO appear earlier in the west coast of Colombia and later in the eastern parts of the country. ENSO anomalies lead the hydrological anomalies by one month in the west, by 2-4 months in central Colombia, and by as much as 6 months in eastern South America, as reported for the Amazon River by Richey et al. (1989) and by Eagleson (1994) for the Trombetas River. The SOI exhibits the largest correlation (Fig. 3) with La Vieja River (Cartago, Valle del Cauca, 4°46'N, 75°54'W) at 1-month lag (0.759), with the Luisa River (Pavo Real, Tolima, 4°13'N, 75°12'W), at 2-months lag (0.59), with Sumapaz River (El Profundo, Cundinamarca 4°00'N, 74°30'W) at 4-months lag (0.637), and with Chivor River (Ubalá, Boyacá, 4°47'N, 73°09'W) at 6-months lag (0.50). All correlations are statistically significant at 95%. These streamflow stations were chosen to have approximately the same latitude, but the progressive delay of the effect, as west longitude decreases, is observed everywhere. As will be discussed later, hydrological processes play a role in determining the velocity at which the anomaly propagates over the continent. Indeed, precipitation, soil moisture, and evapotranspiration anomalies at interannual timescales interact to modulate river discharge anomalies. Figure 4 presents a time-longitude diagram of standardized precipitation anomalies at the interannual timescale in the entire Amazon basin, for the 1972-92 period. Time series have been smoothed using a low-pass 12-month digital filter. Precipitation anomalies appear migrating eastward with time, in the period 1978 through 1981. The El Niño effects during 1976-77, 1982-83, 1986-87, and 1991-92 are evident in Fig. 4, as is the La Niña of 1988-89.

b. Empirical orthogonal functions analyses

EOF analysis is applied to a dataset of rainfall records at 88 stations distributed over Colombia (Fig. 5), which are selected for the quality of their records between 1958 and 1990. The analyses were repeated on monthly, 3-month, and 12-month running averages, following removal of the annual cycle by standardization (difference from the monthly mean divided by the standard deviation of the corresponding month). Up to 46% of the variance can be explained with the first four EOFs, distributed as follows:

EOF no.	1	2	3	4
Explained variance (%)	31	7	4	4
Cumulative variance (%)	31	38	42	46

Figure 6 shows the first two EOFs for the 3-month running mean series of precipitation over Colombia. The

TABLE 1. Lag-zero correlation coefficients (%) between rainfall in Colombia and climatic indices over the Pacific Ocean (12-month running averages).

	Latitude North	Longitude West	-SST N1	-SST N3	-SST N4	Uwin1	-Uwin3	-Uwin4	SOI
Santa Rosa	6.64°	75.45°	25.7	40.6	50.6	25.0	-24.8	47.7	56.1
El Chuscal	6.07°	75.45°	50.0	51.4	57.7	8.9	5.5	65.6	68.2
Rionegro	6.16°	75.35°	45.1	53.6	59.1	16.9	-7.4	64.7	67.5
El Carmen	6.08°	75.32°	27.6	51.1	51.1	28.4	-15.1	60.9	60.9
El Retiro	6.06°	75.51°	40.2	51.5	60.1	13.3	1.9	66.5	70.0
Las Palmas	6.16°	75.53°	39.2	37.5	45.5	6.3	10.4	52.0	55.7
Vasconia	6.21°	75.47°	33.8	45.7	53.1	12.5	1.4	59.1	63.8
Mazo	6.27°	75.50°	42.1	45.0	54.3	7.8	7.4	63.3	64.3
La Mosca	6.31°	75.45°	36.3	40.9	48.6	-1.2	16.3	57.5	58.3
Guatapé	6.25°	75.15°	15.0	35.0	48.1	1.9	25.5	52.8	52.2
Corrientes	6.31°	75.26°	15.6	30.2	34.9	11.5	23.0	45.7	43.6
Ipiales	0.81°	77.63°	18.4	36.3	43.1	10.0	-39.0	41.2	43.7
Obonuco	1.20°	77.30°	33.1	41.6	47.2	-10.4	0.1	49.2	52.3
Sibundoy	1.18°	76.91°	1.3	9.1	20.0	-14.1	14.0	23.6	18.4
Observ. Nal	4.63°	74.10°	20.6	30.0	44.8	3.3	8.0	41.0	41.4
Encino	6.13°	73.11°	49.4	57.4	51.2	26.0	-3.4	54.5	61.4
Cúcuta	7.93°	72.52°	-5.2	-26.5	-1.4	-44.1	56.6	11.4	3.5
Soledad	10.88°	74.78°	45.5	11.3	11.9	-10.6	34.8	33.5	16.1
Cenicafé	4.98°	75.58°	45.9	56.4	54.4	18.9	11.2	59.6	62.5
Pereira	4.82°	75.73°	24.6	31.1	44.4	17.3	-4.4	38.8	44.5
Palmira	3.52°	76.32°	35.0	39.7	51.1	28.2	-22.0	43.0	43.0
Piendamó	2.68°	76.53°	25.2	9.3	27.3	-29.0	29.5	36.9	32.7
Rioabajo	6.25°	75.31°	22.0	37.7	40.4	12.4	13.3	51.6	53.1

first EOF (Fig. 6a), explaining more than 30% of rainfall variability, has the same sign over the entire region, suggesting coherence in regional hydrological behavior at interannual timescales. The corresponding spatial variability broadly represents rainfall response to ENSO forcing, with central and western regions more affected than those on the Caribbean coast and the east. Physical mechanisms associated to the second EOF (Fig. 6b) are not clear, although they could be features of distinctive rainfall forcing either from the Pacific, the Atlantic, and the Amazon basin. The corresponding time series of the first principal component (PC) of rainfall (Fig. 7a) confirms that El Niño events are associated with negative rainfall anomalies and La Niña with positive ones. A Fourier analysis of the first PC also identified important spectral peaks in the frequencies associated to ENSO at 54, 43, and 26 months (Fig. 7b). The origin of the spectral peak at 26 months (Fig. 7b) is an open question, although it could be a manifestation of the influence of the quasi-biennial oscillation (QBO). ENSO exhibits an important quasi-biennial (QB) component, not clearly related to the stratospheric QBO.

Principal components are also computed for monthly river discharges from 55 stations (locations in Fig. 5) in the period 1959–90. All discharges are rescaled by the corresponding monthly standard deviations to facilitate comparison across basin scales. Basins whose rainfall inputs are affected by ENSO, show even higher correlations to SOI than rainfall (see Fig. 1). Basins act as filters to smooth out the variability and intermittency inherent in rainfall, but soil moisture and evapotranspiration are also affected by ENSO via temperature,

wind, and moisture anomalies that vary coherently. The latter concept will be explored more fully.

Figure 8 maps isocorrelations between the SSTs of the Pacific and Indian Oceans and the first principal component of Colombian river discharges. Regions of greatest negative correlations are the central and eastern equatorial Pacific and the area of the Indian monsoon.

c. Discussion

These analyses are consistent with observations of the physical phenomena governing the hydroclimatology of Colombia during the extreme phases of ENSO. El Niño forcing brings low rainfall and discharges, and La Niña is even more strongly related to higher precipitation and streamflows. Correlation analyses suggest that ENSO may explain up to 50% of the observed variance in Colombian hydrology beyond the annual cycle, assuming a linear relationship. Several remarks must be made about these statistics. First, the annual cycle has been removed from both signals, by traditional standardization. Second, smoothed records (3–12-month low-pass filters or running means) are employed to filter out the annual cycle and higher frequencies. Third, all the analysis thus far belongs solely to the linear domain, yet the relationship of ENSO to hydrology is highly nonlinear, and therefore aspects of this type of dependence may be absent. The context of this search for cause-and-effect relationships is more complex than in a simple mechanical system, due to nonlinear interactions between different subsystems (atmosphere, ocean, soil, biosphere, cryosphere) all of

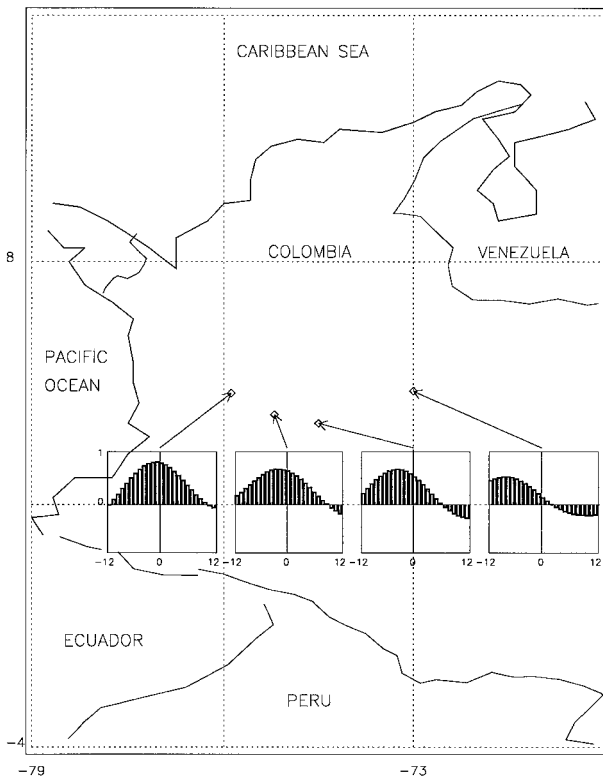


FIG. 3. Behavior of the cross correlations between the SOI and the streamflows of four rivers in Colombia. From west to east: La Vieja (Cartago, Valle del Cauca, $4^{\circ}46'N$, $75^{\circ}54'W$), Luisa (Pavo Real, Tolima, $4^{\circ}13'N$, $75^{\circ}12'W$), Sumapaz (El Profundo, Cundinamarca $4^{\circ}00'N$, $74^{\circ}30'W$), and Chivor (Ubalá, Boyacá, $4^{\circ}47'N$, $73^{\circ}09'W$). Negative lags correspond to the SOI leading the hydrology. Notice that the peaks of the cross correlations occur later as the stations are farther east. The correlations are statistically significant at the 99.9% level.

which change at widely diverging timescales. Finally, the statistical significance of cross correlations is clearly affected by the autocorrelation of each series (Brown and Katz 1991), for that reason significance figures were adjusted according to the scale of fluctuation of the processes (Vanmarcke 1988; Mesa and Poveda 1993).

Correlations between climatic variables over the Pacific Ocean and the Colombian rainfall and runoff series are larger when those lead the Colombian hydrology by 3–4 months. This fact provides good possibilities of developing adequate hydrological predictive models. Certainly, use of such techniques contributes to improve hydrological forecasting, with tremendous practical consequences.

The overall relation between the indices of ENSO and the hydrologic variables is very consistent and physically reasonable, although these statistics suggest only association and are not proof of dependence. There are instances in which rainfall anomalies are not associated with extreme phases of ENSO, and vice versa. The 1982–83 El Niño event is the strongest in the record, but it did not produce intense dry anomalies. During

1957–60 Colombia experienced one of the more prolonged dry seasons in the record, but the 1957–58 El Niño was not particularly marked in either duration or intensity. One of the rainiest years on record (see Fig. 7a) was 1971, which was accompanied by only a moderate La Niña event. Clearly, other factors affect Colombian hydrology besides ENSO, and their dependence is probably nonlinear. A good candidate is the North Atlantic oscillation (NAO), which exhibits significant correlations with the Colombian hydroclimatology (Poveda and Mesa 1996). Moreover, other large-scale climatic phenomena may change the degree, and even the sign of the relation. Discussion of the physical mechanisms involved follows.

3. Feedbacks

It has been observed that the north tropical Atlantic and the Caribbean experience positive, though weaker, anomalies in sea surface temperature during, or after, the warm phase of ENSO (e.g., Covey and Hastenrath 1978; Hastenrath and Wu 1982; Pan and Oort 1983; Halpert and Ropelewski 1992; Curtis and Hastenrath 1995; Nobre and Shukla 1996; Wagner 1996). This warming tends to be stronger during the March–May period. Physical mechanisms that are responsible for the links between the two oceanic basins remain elusive (Lau and Nath 1994), although Curtis and Hastenrath (1995) show that the warming of the tropical Atlantic is the result of wind field perturbations.

We speculate that land–atmosphere interactions over tropical South America contribute to transmitting the signal from the Pacific to the Caribbean and the Atlantic, once El Niño is established. Figure 9 maps correlations between the first principal component of the monthly streamflows (3-month running means, 1959–90) and the SSTs at the Caribbean and the Atlantic, for the hydrology leading the SSTs by 1–6 months. Correlations increase in both absolute value and areal extent when the hydrologic variable leads the SSTs, reaching a maximum at 4–5 months. The region of higher correlation appears to travel eastward with time. Similar correlations (not shown) for the tropical South Atlantic exhibit lower values. By comparison, lagged correlations between the SOI and the SSTs over the Atlantic (Fig. 10) are lower and less extensive. Correlations maps between the Niño-3 SST record and those for the Caribbean and the tropical North Atlantic (not shown) exhibit even lower correlations. These results could be suggesting that precipitation, soil moisture, and evapotranspiration are important mechanisms in establishing the importance of the South American “land–atmosphere bridge,” which would connect the anomalies in the Pacific with those over the Atlantic. There is an imperfect understanding of the physical processes involved in such forcing, but the overall hydrological situation of tropical South America intimates strongly the existence of the bridge.

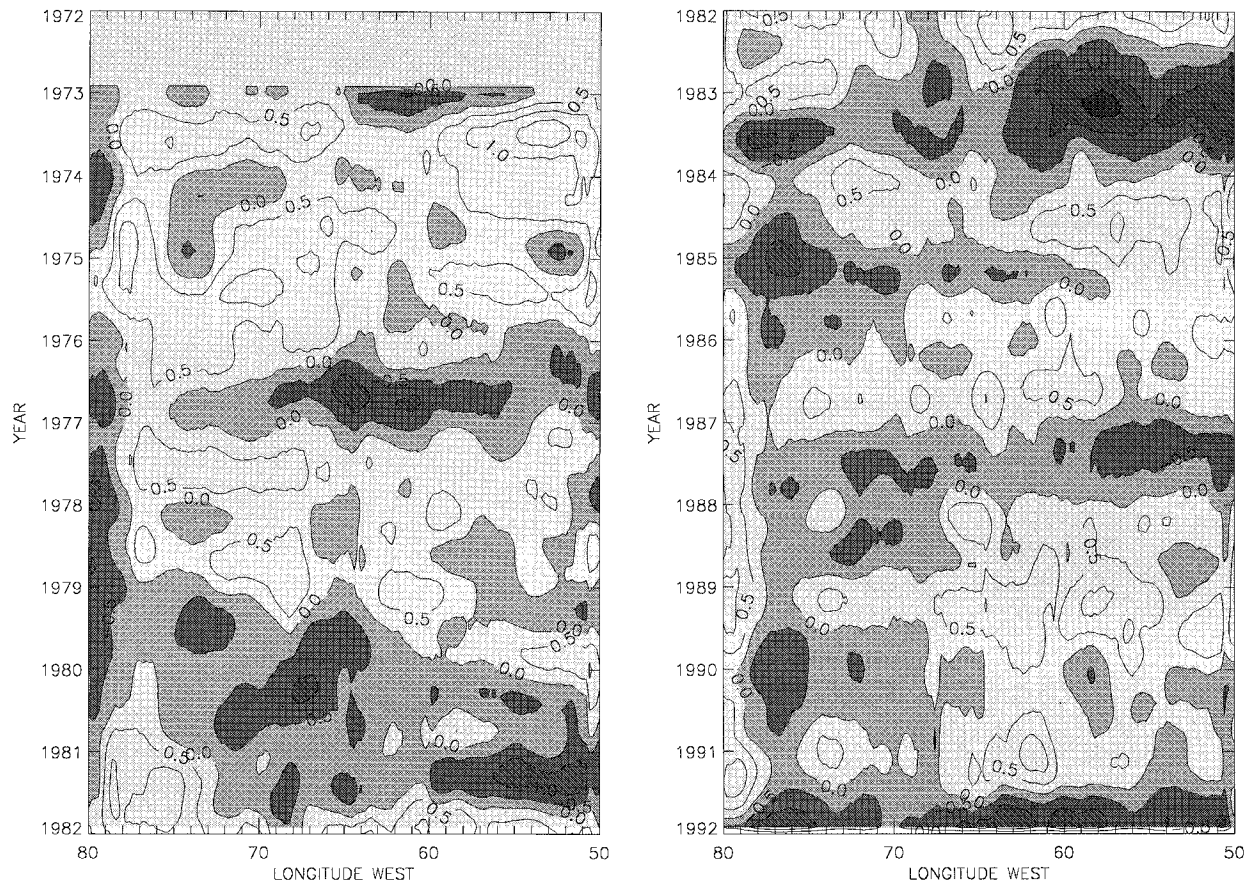


FIG. 4. Time-longitude diagram depicting rainfall anomalies in the whole Amazon basin during the 1972–92 period. Anomalies have been smoothed using a low-pass 12-month digital filter.

We propose the mechanisms to explain the possible influence of tropical South America land-surface process on the north tropical Atlantic SST, at interannual timescales, as follows. The anomalous warming of the Pacific in the Niño-4 and Niño-3 regions acts as a Rossby wave source. The resultant changes in atmospheric circulation produce anomalies in the global circulation that propagate to the east as shown by Yasunari (1987, see his Fig. 7 with the sea level pressure composite anomaly) and Hsu (1994, see his Figs. 1a and 10a showing the global anomalies in OLR). Those oceanic-atmospheric perturbations attain the familiar echelon pattern throughout the central-eastern tropical Pacific, almost symmetrical about the equator, leading toward the Americas and similar to the SST anomalies during El Niño. Notice that the anomalies over tropical South America exhibit an inverse sign to those of the tropical Pacific. Tropical rainfall response is quite different over the Pacific where convection and precipitation are intensified during El Niño events, while negative anomalies prevail over continental South America.

Anomalous high surface pressure is established in tropical South America [Fig. 11.27a of Gill (1982), Fig. 7 of Yasunari (1987), and Fig. 5 of Aceituno (1988)],

particularly during the DJF period, seemingly the result of an anomalous Hadley cell that subdues the ascent of moist air and the associated convection and precipitation. This pattern appears as a common feature of ENSO, because it has been identified during El Niño events of 1982–83, 1986–87, and 1991–92 (Rasmusson and Mo 1993). The areal extent of those anomalies is much more broader than tropical South America. That very observation confirms the importance of the interaction between the land and atmosphere in tropical South America to influence the tropical Atlantic circulation. The impact of interannual variability of the land-atmosphere system in tropical South America is so large that the whole upper-atmospheric circulation and the divergent flux are perturbed beyond its frontiers. There are modeling results (Zeng et al. 1996) that suggest that deforestation scenarios of the Amazon basin (in many ways similar to the effects of the warm phase of ENSO), would produce a weakening of the sea surface temperature gradient along the tropical Atlantic Ocean, and also it could affect the global atmospheric circulation through perturbations of both the Walker and the Hadley cells (Zhang et al. 1996). Indeed, rainfall in the Amazon basin has been recognized as a modulator

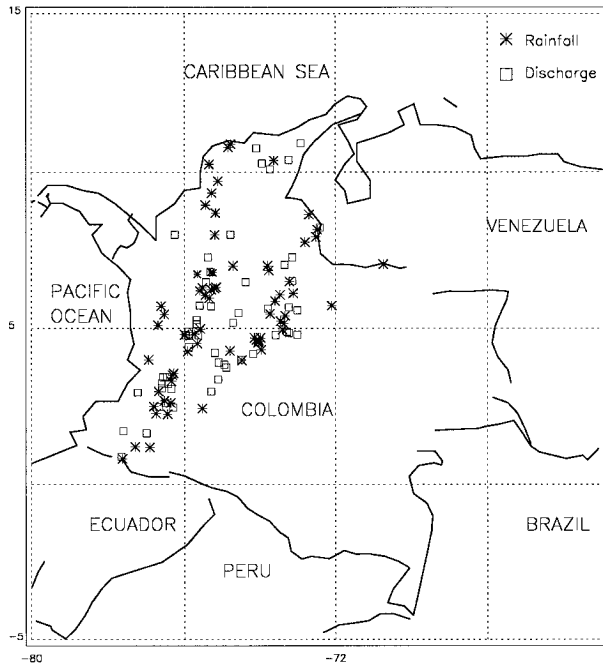


FIG. 5. Location in Colombia of the 88 rainfall stations and the 55 river discharge stations included in the separated EOF analyses.

of convection in the Atlantic ITCZ and over the eastern Pacific (Silva Dias et al. 1987).

The anomalous increase in sea level pressure over tropical South America during El Niño contributes to

the displacement and maintenance of the center of convection of the ITCZ toward the west and the south of its normal position (Pulwarty and Diaz 1993). During El Niño, the meridional gradient of SST between Colombian coastal waters and the cold tongue diminishes. This produces a decrease in the low-level cross-equatorial westerlies winds and the advection of moisture from the Pacific thus contributing to the drought. On top of that, there is a reduction in Atlantic weather systems activity over northern South America (Frank and Hebert 1974; Gray and Sheaffer 1991), thereby decreasing moisture advection and precipitation events over northern South America, including Colombia. Thus, El Niño could contribute to cooling of the troposphere over this region due to a decrease in the release of latent heat of condensation associated with negative anomalous precipitation, despite the surface warming due to decreased evaporation and cloudiness (see Fig. 2a of Nigam 1994).

The interannual anomalies in precipitation (Lau and Sheu 1988; Hsu 1994; Kousky and Kayano 1994) force negative anomalies in soil moisture, at the same time-scale. In tropical South America this fact has been reported by Nepstad et al. (1994) and by Jipp et al. (1997), from experimental data gathered in the Amazon basin forests and pastures: soil moisture deficits associated to the 1991–92 El Niño event persisted until 1994. The obvious hydrological connection between soil moisture and river discharges validates the conclusions drawn from the isocorrelation maps shown in Fig. 9. Modeling

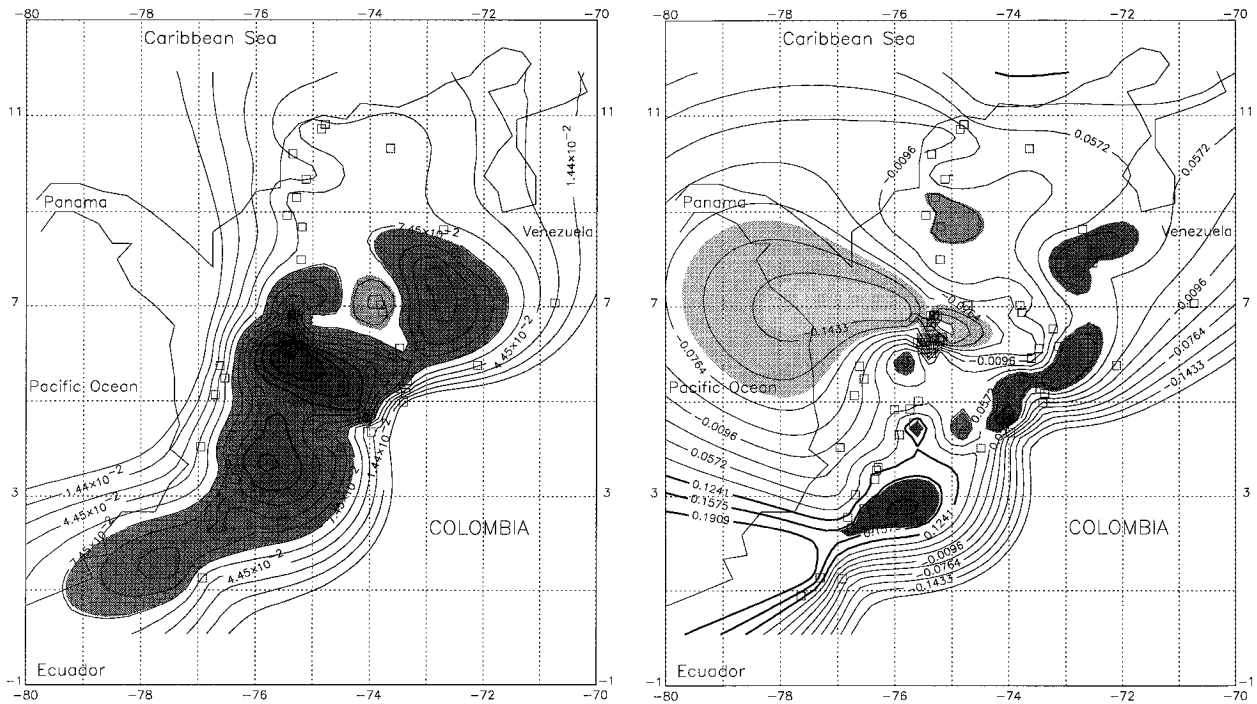


FIG. 6. The first two EOFs for the Colombian monthly rainfall (3-month running means), which explain 30.7% and 6.5% of the total variance, respectively.

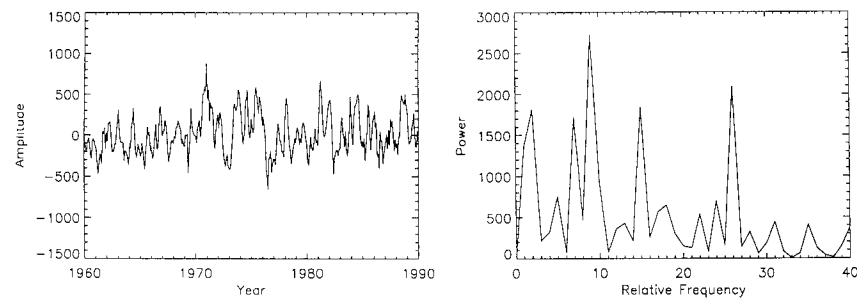


FIG. 7. (a) Time series of the first principal component (PC) for the Colombian streamflow river discharges. Monthly values have been smoothed as 3-month running means. (b) Fast Fourier transform of the first PC. Frequency is relative to the total record length (396 months), and the corresponding period (months) is estimated as $396/\text{relative frequency}$.

results confirm the interannual modulation of soil moisture at ENSO timescales. Temporal variability of monthly soil moisture anomalies in tropical South America has been examined through estimates of average ground wetness (a ratio of soil moisture to the maximum moisture, w/ws , $ws = 150$ mm) for the globe (see details in Schemm et al. 1992). Figure 11 presents the temporal evolution of monthly average ground wetness anomalies over the Amazon, Orinoco, and Magdalena River basins for the period 1979–92. Data have been smoothed using a 12-month low-pass filter (thick line). Long-term persistent behavior of soil moisture at the interannual scale is clearly observed, as are the modulation of soil moisture by the El Niños of 1982–83 and 1986–87 and by the La Niña of 1988.

Due to soil moisture depletion during El Niño, evapotranspiration rates are also reduced. This affects the partitioning of the surface energy balance, especially between latent and sensible heating. Nepstad et al. (1994) report a 28% reduction in evapotranspiration during an El Niño (1992–93), compared to non-El Niño years (1991 and 1994) over Amazonian forests and a 42% decline above pastures. Evapotranspiration is clearly reduced in pastures and secondary forests of the Amazon basin during dry seasons, in particular during those forced by El Niño (Hodnett et al. 1996). Similar reductions in evapotranspiration are reported by Vörösmarty et al. (1996) from water balance estimates for the

whole Amazon River basin during the period September 1983–August 1984, following the 1982–1983 El Niño event. Interannual anomalies in soil moisture and evapotranspiration are more critical than those caused by the annual cycle. Assuming that during normal years water is not the limiting factor to determine the Bowen ratio, the Amazon basin could be seen as an ocean. During ENSO events, water can be the limiting factor, due to the amplitude and length of the dry period, and therefore its anomaly is much more critical. As a consequence, the system responds in a completely different manner.

Reductions in evapotranspiration lead to further precipitation deficits, as large proportions (35%–50%) of rainfall in the Amazon basin are believed to be derived from evapotranspiration recycling (Shuttleworth 1988; Elthair and Bras 1994). This is a crucial aspect of the feedback mechanisms of land–atmosphere interactions during ENSO over tropical South America. The latent heat released into the atmosphere over the Amazon basin during La Niña events is approximately 190 W m^{-2} (1988–89) and reduces to 150 W m^{-2} in El Niño events (1991–92). Precipitation reduction is also consistent with the development of an anomalous position and direction of the Hadley cell toward the equator. Implicit here is the existence of a positive feedback effect between the tropical precipitation and the Hadley circulation (Numaguti 1993).

During the warm phase of ENSO, the cooperative

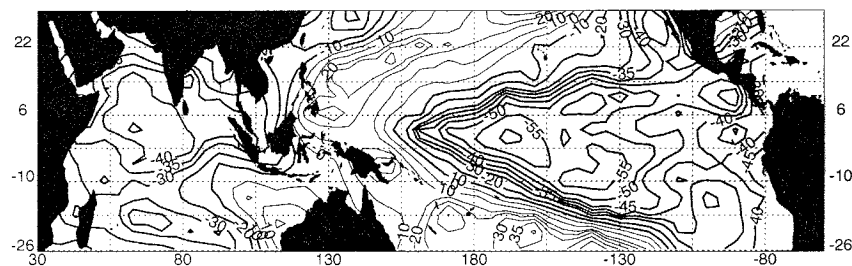


FIG. 8. Isocorrelations (%) between sea surface temperatures at each location and the first principal component of the Colombian monthly streamflows (3-month running averages). Notice the high values of the correlation coefficients at the regions of the central Pacific Ocean and the region of the Indian monsoon.

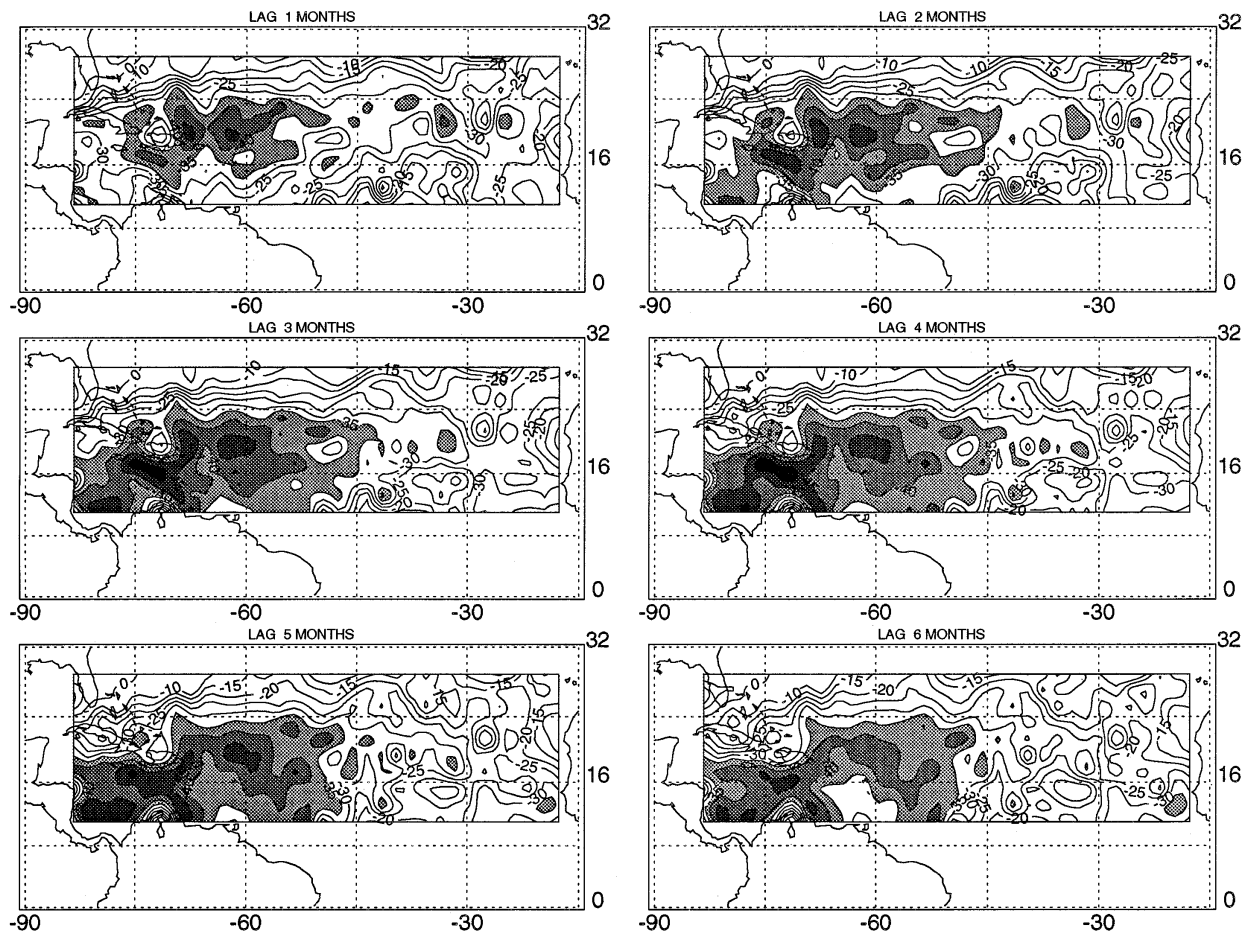


FIG. 9. Lagged isocorrelations (%) between the first principal component of the Colombian river discharges (3-month running means) and sea surface temperatures at each location. Streamflows are leading the Atlantic SSTs from 1 to 6 months. Notice that the region of larger correlations is traveling eastward and gaining areal extent with time, and peaks at 4–5 months.

effect of a lower sea level pressure in the North Atlantic (Nobre and Shukla 1996) and the increased surface atmospheric pressure in tropical South America contributes to reduce the surface pressure gradient between the two regions. Figure 12 presents the time series of standardized anomalies for both the mean sea level pressure gradient between the Azores Islands (25° – 35° W, 30° – 40° N) and northern South America (50° – 70° W, 3° S– 10° N), as well as precipitation over the latter region, for the period 1982–94, as obtained from the The National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis project. It can be seen that negative precipitation anomalies over the region are well associated to anomalous negative sea level pressure gradient (lower North Atlantic High and higher tropical South America). These mechanisms in turn contribute to the weakening of the northeast trades, triggering oceanic warming over the Caribbean and the north tropical Atlantic.

Coupling between the reduction (enhancement) of the easterly trade winds and warming (cooling) of the tropical north Atlantic and pressure gradient reduction (in-

creasing) during or after the warm (cold) phase of ENSO has been reported by Horel et al. (1986), Marengo (1992), Pulwarty (1994), Curtis and Hastenrath (1995), and Nobre and Shukla (1996). Interestingly, Carton and Huang (1994) argue that during the Atlantic warm events the ocean acts as a passive guide through which heat is shifted from west to east in response to changes in the wind field. This kind of eastward displacement would be manifest in the correlation maps of Fig. 9. The observations and the proposed mechanisms presented here are also in agreement with the suggestion of Zebiak (1993) that SST variability over the tropical Atlantic may be related to land–surface interactions and to large-scale forcing related to ENSO, and also with the proposed positive feedback between land–surface and atmospheric processes in the South America–Atlantic ocean–atmospheric circulation (Zeng et al. 1996). Once the SSTs increase over the Caribbean and the north tropical Atlantic, coupled ocean–atmosphere phenomena carry the signal through the rest of the Atlantic toward Africa, as suggested by Carton and Huang (1994).

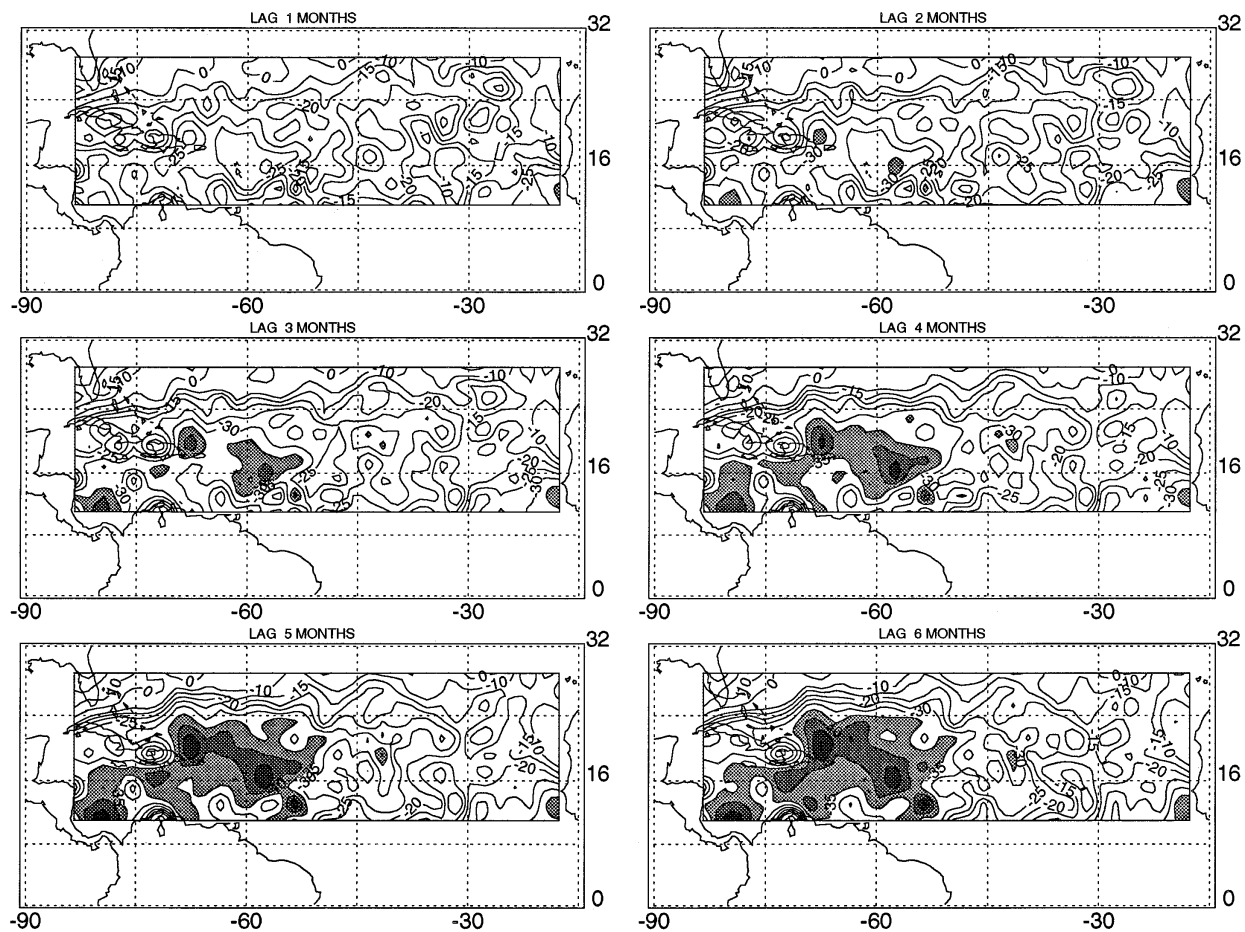


FIG. 10. Lagged isocorrelations (%) between the Southern Oscillation index (SOI) and sea surface temperatures at each location. SOI is leading the SSTs from 1 to 6 months. Notice that the correlations are lower than those shown in Fig. 9.

4. Conclusions

Large-scale coupled ocean–atmosphere phenomena force hydrologic anomalies in tropical South America at interannual scales. Extensive data analyses illustrate the influence of ENSO on the hydrology of tropical South America. Broadly, El Niño stimulates dry periods and La Niña is associated with excessive moisture, rainfall, and river discharges. The impact of La Niña is stronger than El Niño’s impact. Because of multiple nonlinear interactions among diverse geophysical phenomena, the relationship is not a simple one, exhibiting differences in amplitude, timing, and duration, but the zero-order effect is clear. There is evidence of an eastward propagation of ENSO effects in streamflow in Colombian and other tropical South American rivers. The situation over the Atlantic is also important in modulating the influence of ENSO over the region, as the North Atlantic oscillation exhibits an interesting coupling with the hydrometeorology of tropical South America. The influence of large-scale ocean–atmosphere phenomena on hydrologic anomalies needs to be accounted for in water resources systems planning, and

management. In the past, during droughts associated with El Niño, Colombia has attempted cloud seeding to sustain reservoir levels (López 1966). The 1991–92 El Niño event caused losses of about \$1 billion to the national economy, due to prolonged electricity shortages forced by the drought. Colombia now carefully monitors the evolution of the climatic situation, especially over the Pacific, with a view to the operation of its water resource systems and their future expansion.

Hydrological anomalies are not passive spectators of the “surrounding climate” but can contribute to its shaping. The case of tropical South America is an example of such feedback. We have hypothesized the mechanisms by which the hydrology of tropical South America plays an important role in constructing the “land–atmosphere bridge” connecting SST in the Pacific to those of the tropical north Atlantic and Caribbean, once an El Niño event develops. In particular, surface pressure, precipitation, temperature, evapotranspiration, soil moisture, and river runoff are highly interconnected in a coherent system. The resulting effect would produce weakening of the trade wind field that

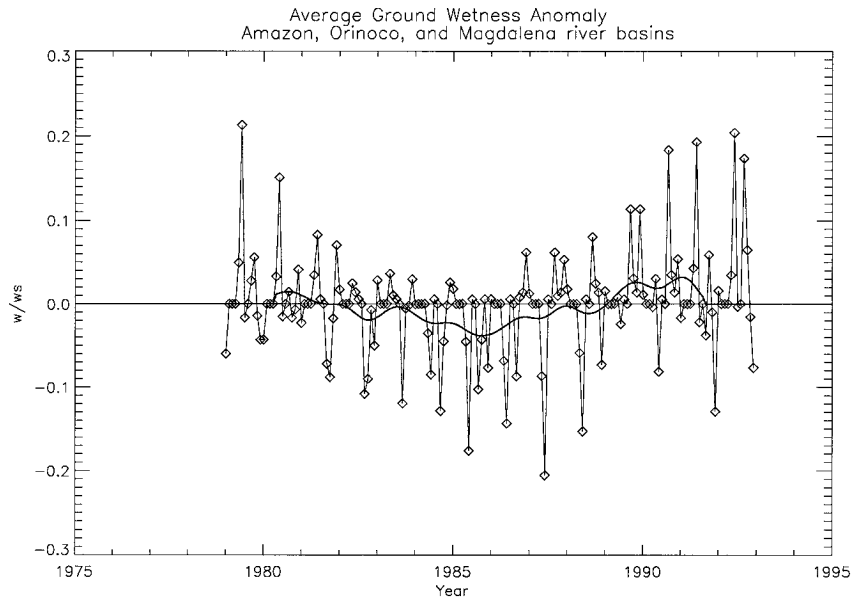


FIG. 11. Time evolution of monthly average ground wetness anomalies for the combined Amazon, Orinoco, and Magdalena River basins during 1979–92. Monthly averages have been smoothed using a 12-month low-pass filter (thick line).

ultimately contributes to the warming of the Caribbean and the tropical North Atlantic. Dry conditions induced by El Niño are self-reinforced through the dynamics of precipitation recycling and hydrological processes over the region. Soil moisture over the continent plays a similar role that of sea surface temperature over the oceans in driving the dynamical partition of water and energy budgets at the land–atmosphere and ocean–atmosphere interfaces, respectively. This paper presents evidence of long-term persistent behavior of soil moisture anomalies at interannual timescales over the Amazon, Orinoco, and Magdalena River basins, which suggest that soil moisture over the region is an important component of

ENSO. More detailed soil moisture datasets need to be collected and analyzed over the region to confirm these results.

Acknowledgments. Support from COLCIENCIAS of Colombia is gratefully acknowledged. Part of this work was developed while the authors were on leave at CIRES/CSES, University of Colorado, Boulder. Colombian hydrology data were provided by IDEAM and EPM of Colombia. The COADS dataset is from NOAA. Amazon rainfall data are from the EOS-Amazon Project. The soil moisture dataset was provided by J. Schemm (NASA). We thank V. K. Gupta, C. Penland, H. F. Diaz, K. Weickman, K. Trenberth, C. Ropelewski, P. Webster, S. Hastenrath, P. Aceituno, E. A. Davidson, R. Newell, and P. R. Waylen for fruitful discussions and the two anonymous reviewers for helpful comments.

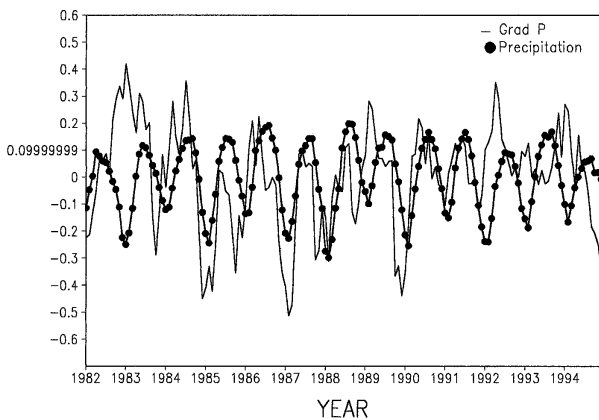


FIG. 12. Time evolution of standardized anomalies for the mean sea level pressure gradient between the Azores Islands (25°–35°W, 30°–40°N) and northern South America (50°–70°W, 3°S–10°N), and precipitation over the latter region, for the period 1982–94. Data from the NCEP–NCAR reanalysis project.

REFERENCES

Aceituno, P., 1988: On the functioning of the Southern Oscillation in the South American sector. Part I: Surface climate. *Mon. Wea. Rev.*, **116**, 505–524.

—, 1989: On the functioning of the Southern Oscillation in the South American sector. Part II: Upper-air circulation. *J. Climate*, **2**, 341–355.

Baumgartner, A., and E. Reichel, 1975: *The World Water Balance*. Elsevier, 179 pp.

Brown, B. G., and R. W. Katz, 1991: Use of statistical methods in the search for teleconnections; Past, present and future. *Teleconnections Linking Worldwide Climate Anomalies*, R. M. Glantz, R. Katz, and N. Nicholls, Eds., Cambridge University Press, 371–400.

Carton, J. A., and B. Huang, 1994: Warm events in the tropical Atlantic. *J. Phys. Oceanogr.*, **24**, 888–903.

Chu, P.-S., 1991: Brazil’s climate anomalies and ENSO. *Teleconnec-*

- tions Linking Worldwide Climate Anomalies, R. M. Glantz, R. Katz, and N. Nicholls, Eds., Cambridge University Press, 43–71.
- Covey, D., and S. Hastenrath, 1978: The Pacific El Niño phenomenon and the Atlantic circulation. *Mon. Wea. Rev.*, **106**, 1280–1287.
- Curtis, S., and S. Hastenrath, 1995: Forcing of anomalous sea surface temperature evolution in the tropical Atlantic during Pacific warm events. *J. Geophys. Res.*, **100** (C8), 15 835–15 847.
- Diaz, H. F., and V. Markgraf, Eds., 1992: *El Niño. Historical and Paleoclimatic Aspects of the Southern Oscillation*. Cambridge University Press, 476 pp.
- Eagleson, P. E., 1994: The evolution of modern hydrology (from watershed to continent in 30 years). *Adv. Water Res.*, **17**, 3–18.
- Elthair, E. A. B., and R. Bras, 1994: Precipitation recycling in the Amazon basin. *Quart. J. Roy. Meteor. Soc.*, **120**, 861–880.
- Estoque, M. A., J. Luque, M. Chandek-Monteza, and J. García, 1985: Effects of El Niño on Panama rainfall. *Geofis. Int.*, **24**, 355–381.
- Frank, N. L., and P. J. Hebert, 1974: Atlantic tropical systems of 1973. *Mon. Wea. Rev.*, **102**, 290–295.
- Gessler, R. D., 1995: Precipitation variability over Ecuador associated with the El Niño/Southern Oscillation. M.S. thesis, Dept. of Geography, University of Florida, 85 pp. [Available from P. Waylen, Dept. of Geography, University of Florida, Gainesville, FL 32611-7315.]
- Gill, A. E., 1982: *Atmosphere–Ocean Dynamics*. Academic Press, 662 pp.
- Glantz, M., R. Katz, and N. Nicholls, Eds., 1991: *Teleconnections Linking Worldwide Climate Anomalies*. Cambridge University Press, 535 pp.
- Gray, W. M., and J. D. Sheaffer, 1991: El Niño and QBO influences on tropical cyclone activity. *Teleconnections Linking Worldwide Climate Anomalies*, R. M. Glantz, R. Katz, and N. Nicholls, Eds., Cambridge University Press, 257–284.
- Halpert, M. S., and C. F. Ropelewski, 1992: Surface temperature patterns associated with the Southern Oscillation. *J. Climate*, **5**, 577–593.
- Hastenrath, S., 1976: Variations in low-latitude circulations and extreme climatic events in the tropical Americas. *J. Atmos. Sci.*, **33**, 202–215.
- , 1990: Diagnostic and prediction of anomalous river discharges in northern South America. *J. Climate*, **3**, 1080–1096.
- , and M.-C. Wu, 1982: Oscillations of the upper-air circulation and anomalies in the surface climate of the tropics. *Arch. Meteor. Geophys. Bioclimatol., Ser. B*, **31**, 1–37.
- , and L. Greischar, 1993: Further work on the prediction of northeast Brazil rainfall anomalies. *J. Climate*, **6**, 743–758.
- Hodnett, M. G., M. D. Omayya, J. Tomasella, and A. de O. Marques Filho, 1996: Comparisons of long-term soil water storage behaviour under pasture and forest in three areas of Amazonia. *Amazonian Deforestation and Climate*, J. H. C. Gash, C. A. Nobre, J. M. Roberts, and R. L. Victoria, Eds., Wiley and Sons, 57–77.
- Horel, J. D., and J. M. Wallace, 1981: Planetary scale atmospheric phenomena associated with the Southern Oscillation. *Mon. Wea. Rev.*, **109**, 813–829.
- , V. E. Kousky, and M. T. Kayano, 1986: Atmospheric conditions in the Atlantic sector during 1983 and 1984. *Nature*, **322**, 248–251.
- Hsu, H.-H., 1994: Relationship between tropical heating and global circulation, Interannual variability. *J. Geophys. Res.*, **99**(D5), 10 473–10 489.
- Jipp, P. H., D. C. Nepstad, D. K. Cassel, and C. R. de Carvalho, 1997: Deep soil moisture storage and transpiration in forests and pastures of seasonally-dry Amazonia. *Climate Change*, in press.
- Kayano, M. T., V. B. Rao, and A. D. Moura, 1988: Tropical circulations and the associated rainfall anomalies during two contrasting years. *J. Climatol.*, **8**, 477–488.
- Kiladis, G., and H. F. Diaz, 1989: Global climatic anomalies associated with extremes in the Southern Oscillation. *J. Climate*, **2**, 1069–1090.
- Kousky, V. E., and M. T. Kayano, 1994: Principal modes of outgoing longwave radiation and 250-mb circulation for the South American sector. *J. Climate*, **7**, 1131–1143.
- , —, and I. F. A. Cavalcanti, 1984: A review of the Southern Oscillation: Oceanic atmospheric circulation changes and related rainfall anomalies. *Tellus*, **36A**, 490–504.
- Lau, K. M., and P. J. Sheu, 1988: Annual cycle, quasi-biennial oscillation, and Southern Oscillation in global precipitation. *J. Geophys. Res.*, **93**(D9), 10 975–10 989.
- Lau, N.-C., and M. J. Nath, 1994: A modeling study of the relative roles of tropical and extratropical SST anomalies in the variability of the global atmosphere-ocean system. *J. Climate*, **7**, 1184–1207.
- López, M. E., 1966: Cloud seeding trials in the rainy belt of western Colombia. *Water Resour. Res.*, **2**, 811–823.
- , and W. E. Howell, 1967: Katabatic winds in the equatorial Andes. *J. Atmos. Sci.*, **24**, 29–35.
- Marengo, J., 1992: Interannual variability of surface climate in the Amazon basin. *J. Climatol.*, **12**, 853–863.
- , and S. Hastenrath, 1993: Case studies of extreme climatic events in the Amazon basin. *J. Climate*, **6**, 617–627.
- Mesa, O. J., and G. Poveda, 1993: The Hurst effect: The scale of fluctuation approach. *Water Resour. Res.*, **29**, 3995–4002.
- Nepstad, D. C., and Coauthors, 1994: The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. *Nature*, **372**, 666–669.
- Nigam, S., 1994: On the dynamical basis for the Asian monsoon rainfall–El Niño relationship. *J. Climate*, **7**, 1750–1771.
- Nobre, P., and J. Shukla, 1996: Variations of sea surface temperature, wind stress, and rainfall over the tropical Atlantic and South America. *J. Climate*, **9**, 2464–2479.
- Numaguti, A., 1993: Dynamics and energy balance of the Hadley circulation and the tropical precipitation zones: Significance of the distribution of evaporation. *J. Atmos. Sci.*, **50**, 1874–1887.
- Obregón, G. O., and C. A. Nobre, 1990: Principal component analysis of precipitation fields over the Amazon river basin. *Climanálise*, **5**, 35–46.
- Pan, Y. H., and A. H. Oort, 1983: Global climate variations connected with the sea surface temperature anomalies in the eastern equatorial Pacific Ocean for the 1958–73 period. *Mon. Wea. Rev.*, **111**, 1244–1258.
- Poveda, G., 1994: Empirical orthogonal functions in the analysis of the relationship between mean discharges in Colombia and the Pacific and Atlantic Oceans surface temperatures (in Spanish). *Proc. XVI Latin-American Congress on Hydraulics and Hydrology*, Vol. 4, Santiago, Chile, IAHS, 131–144.
- , and O. J. Mesa, 1993: Methodologies to predict the Colombian hydrology considering the ENSO event (in Spanish). *Rev. Atmos.*, **16**, 26–39.
- , and —, 1995: The relationship between ENSO and the hydrology of tropical South America. The case of Colombia. *Proc. Fifteenth Annual American Geophysical Union Hydrology Days*, Fort Collins, CO, Hydrology Days Publications, 227–236. [Available from H. Morel-Seytoux, 57 Selby Lane, Atherton, CA 94027-3926.]
- , and —, 1996: The North Atlantic Oscillation and its influence on the hydro-climatology of Colombia (in Spanish). *Proc. XVII Latin-American Congress on Hydraulics and Hydrology*, Vol. II, Guayaquil, Ecuador, IAHR, 343–354.
- Pulwarty, R. S., 1994: Annual and intrannual variability of convection over tropical South America. Ph.D. dissertation, University of Colorado, 220 pp. [Available from Dept. of Geography, University of Colorado, Boulder, CO 80305.]
- , and H. F. Diaz, 1993: A study of the seasonal cycle and its perturbation by ENSO in the tropical Americas. Preprints, *Fourth Int. Conf. on Southern Hemisphere Meteorology and Oceanography*, Hobart, Australia, Amer. Meteor. Soc., 262–263.

- , R. G. Barry, and H. Riehl, 1992: Annual and seasonal patterns of rainfall variability over Venezuela. *Erdkunde*, **46**, 273–289.
- Rao, V. B., and K. Hada, 1990: Characteristics of rainfall over Brazil: Annual variations and connections with the Southern Oscillation. *Theor. Appl. Climatol.*, **42**, 81–91.
- Rasmusson, E. M., 1991: Observational aspects of ENSO cycle teleconnections. *Teleconnections Linking Worldwide Climate Anomalies, Scientific Basis and Societal Impacts*, M. Glantz, R. W. Katz, and N. Nicholls, Eds. Cambridge University Press, 309–343.
- , and T. H. Carpenter, 1982: Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation. *Mon. Wea. Rev.*, **110**, 354–384.
- , and K. Mo, 1993: Linkages between 200-mb tropical and extratropical circulation anomalies during the 1986–1989 ENSO cycle. *J. Climate*, **6**, 595–616.
- Richey, J. E., C. Nobre, and C. Deser, 1989: Amazon river discharge and climate variability: 1903 to 1985. *Science*, **246**, 101–103.
- Riehl, H., and J. S. Malkus, 1958: On the heat balance in the equatorial trough zone. *Geophysica*, **6**, 505–538.
- Rogers, J. C., 1988: Precipitation variability over the Caribbean and tropical Americas associated with the Southern Oscillation. *J. Climate*, **1**, 172–182.
- Ropelewski, C. F., and M. S. Halpert, 1987: Global and regional scales precipitation associated with El Niño–Southern Oscillation. *Mon. Wea. Rev.*, **115**, 1606–1626.
- Schemm, J., S. Schubert, J. Terry, and S. Bloom, 1992: Estimates of monthly mean soil moisture for 1979–1989. NASA Tech. Memo. 104571, Goddard Space Flight Center, Greenbelt, MD, 252 pp. [Available from S. Schubert, Goddard Space Flight Center, Greenbelt, MD 20771.]
- Shuttleworth, W. J., 1988: Evaporation from Amazonian rainforest. *Philos. Trans. Roy. Soc. London, Ser. B*, **233**, 321–346.
- Silva Dias, P. L., J. P. Bonatti, and V. E. Kousky, 1987: Diurnally forced tropical tropospheric circulation over South America. *Mon. Wea. Rev.*, **115**, 1465–1478.
- Slutz, R. J., S. J. Lubker, J. D. Hiscox, S. D. Woodruff, R. L. Jenne, D. H. Joseph, P. M. Steurer, and J. D. Elms, 1985: Comprehensive Ocean–Atmosphere Data Set, release 1. NOAA Tech. Note, 255 pp. [Available from University of Colorado/National Oceanic and Atmospheric Administration, Cooperative Institute for Research in Environmental Sciences, Boulder, CO 80305.]
- Trenberth, K., 1991: General characteristics of El Niño–Southern Oscillation. *Teleconnections Linking Worldwide Climate Anomalies*, R. M. Glantz, R. Katz, and N. Nicholls, Eds., Cambridge University Press, 13–42.
- van Loon, H., and R. A. Madden, 1981: The Southern Oscillation, I. Global associations with pressure and temperature in northern winter. *Mon. Wea. Rev.*, **109**, 1150–1162.
- Vanmarcke, E., 1988: *Random Fields: Analysis and Synthesis*. The MIT Press, 382 pp.
- Velasco, I., and M. Fritsch, 1987: Mesoscale convective complexes in the Americas. *J. Geophys. Res.*, **92**(D8), 9591–9613.
- Vörösmarty, C. J., C. J. Willmott, B. J. Choudhury, A. L. Schloss, T. K. Stearns, S. M. Robeson, and T. J. Dorman, 1996: Analyzing the discharge regime of a large tropical river through remote sensing, ground-based climatic data, and modeling. *Water Resour. Res.*, **32**, 3137–3150.
- Wagner, R. C., 1996: Mechanisms controlling variability of the interhemispheric sea surface temperature gradient in the tropical Atlantic. *J. Climate*, **9**, 2010–2019.
- Waylen, P. R., C. N. Caviedes, and M. E. Quesada, 1996: Interannual variability of monthly precipitation in Costa Rica. *J. Climate*, **9**, 2606–2613.
- Yasunari, T., 1987: Global structure of the El Niño/Southern Oscillation Part I. El Niño composites. *J. Meteor. Soc. Japan*, **65**, 67–79.
- Zebiak, S. E., 1993: Air–sea interaction in the equatorial Atlantic region. *J. Climate*, **6**, 1567–1586.
- Zeng, N., R. E. Dickinson, and X. Zeng, 1996: Climatic impact of Amazon deforestation—A mechanistic model study. *J. Climate*, **9**, 859–883.
- Zhang, H., K., McGuffie, and A. Henderson-Sellers, 1996: Impacts of tropical deforestation. Part II: The role of large-scale dynamics. *J. Climate*, **9**, 2498–2521.