JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. D2, PAGES 1775–1783, JANUARY 27, 1998

Trends in streamflow and rainfall in tropical South America: Amazonia, eastern Brazil, and northwestern Peru

José A. Marengo and Javier Tomasella
Centro de Previsão de Tempo e Estudos Climáticos, CPTEC/INPE, Cachoeira Paulista, São Paulo, Brazil

Cintia R. Uvo
Department of Water Resources Engineering, Lund University, Lund, Sweden

Abstract. Long hydrological records, from the Amazon Basin, northeastern Brazil, and northwestern Peru spanning most of this century, are examined for trends in rainfall (three wettest months) and runoff (three months of highest flow) or stage, where no rating curves exist. Trends are tested for significance using the Mann-Kendall statistic. In basins where large soil, aquifer, or man-made reservoirs give rise to appreciable over-year storage, flows and water levels may be serially correlated. Where serial correlation exists, the usual statistical tests (linear regression, t-test, and Mann-Kendall) will overestimate the significance of trends, showing significance where none exists. Analysis for trend therefore requires particular care when data are serially correlated, and to avoid misleading results, additional supportive evidence must be sought. For example, rainfall records within the same river basin can be checked for trends; serial correlation in rainfall records, in particular, is less likely to be present, so the validity of any trends in rainfall is less open to question. Strong negative trends were found in flow data from the coast of northern Peru and the São Francisco River, while positive significant trends were detected in the Parnaíba River basin. No significant trends were found in the discharge or stage records from Amazonia, while rainfall in northeastern Brazil shows a slow increase over long periods. In the Parnaíba and in some rivers of northern Peru unusually large discharges at the beginning or end of the records seem to account for the direction and significance of trends.

1. Introduction

Since river flow is largely the result of rainfall and evaporation, it is a measure of climate variability both intra-annually and interannually, since periods of above-average rainfall tend to be followed by periods of above-average runoff. However, interpretation of trends in streamflow as indicators of climate change is complicated by several factors: changes in land use, runoff increases after deforestation [*Bruinjzeel*, 1996]; construction of impoundments, which divert flow to irrigated land where evaporation losses are greater; runoff records are generally shorter than those of rainfall and temperature, which are both "input" variables of the resulting streamflow; and gradual changes in river bed formation through erosion or sediment deposition, which may be ignored in calculating the rating curves used to estimate discharge from water level (stage).

There is another often ignored difficulty: namely, that in river basins where there is appreciable storage in soil and aquifers, a proportion of the rain falling in any year may be released in subsequent years, so that mean annual flows are serially correlated. Years with above average rainfall may be followed by several years of above average runoff, and vice versa. Ignoring the serial correlations causes statistical tests to overestimate the significance of trends [*Box et al.*, 1968].

Streamflow records that are most likely to show serial correlation are those from large, well-watered drainage basins with extensive storage. Rainfall records, on the other hand, are much less likely to be complicated by serial correlation, since atmospheric processes have a shorter memory than large river basins.

In previous studies using flow records, no clear trends were found which might be explained by regional climate change [*Lettenmaier et al.*, 1994; *Chiew and McMahon*, 1993; *Marengo*, 1992, 1995; *Richey et al.*, 1989]. Analysis of South American rainfall records has not produced clear results: with some analysis indicating no trends [*Marengo*, 1995; *Hastenrath and Greischar*, 1993], others suggesting weak trends [*Dias de Paiva and Clarke*, 1995], and others finding periods of change within the record [*Chu et al.*, 1994; *Marengo*, 1992; *Gentry and Lopez-Parodi*, 1980, 1982; *Rocha et al.*, 1989]. However, the records analyzed were of limited length, giving rise to the further difficulty of distinguishing trend from low-period fluctuations.

In this paper, we analyze and consider the impact of serial correlation on the long-term records of streamflow, water levels, and rainfall in the Amazon Basin, eastern Brazil, and the northwestern coast of Peru to assess whether there is evidence of long-term trends that might indicate climatic change.

2. Streamflow and Rainfall Data and Analysis

Figure 1 presents the location of the gauging stations in Amazonia, eastern Brazil, and northwestern Peru. The river gauging sequences extend from 30 to 90 years of continuous records and rainfall sequences, for more than 60 years in eastern Brazil and Amazonia, while shorter, less complete series were obtained from northern Peru. In addition, the Southern

Paper number 97JD02551
0148-0227/98/97JD-02551$09.00

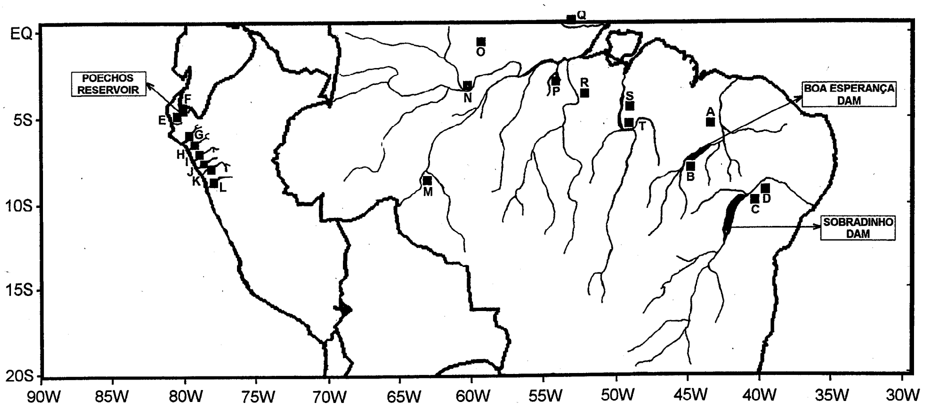

Figure 1. Map showing the Amazon Basin (including the Tocantins River), northeastern Brazil, and northwestern Peru. Squares indicate the river gauging stations; letters show gauge sites and river names as listed in Table 1.

Oscillation Index (SOI), defined as the pressure difference of Tahiti (18°S, 150°W) minus Darwin (12°S, 131°W) during 1903–1992, was used in this study.

The analysis assumes that flow and water level records are free from problems caused by sediment accumulation, erosion, and local changes of gauge site. The INRENA [*Instituto Nacional de Recursos Naturales* (*INRENA*), 1994] and ELETROBRAS gauging stations are unaffected by upstream regulation and should show trends, if any exist. For flow (or stage) records the 3 month period was identified in which accumulated runoff (mean stage) was a maximum; similarly, for the rainfall records the 3 month period of highest rainfall was identified. Subsequent statistical analyses are focused on data from the 3 month maxima.

The direction and statistical significance of trends were determined by using the Mann-Kendall statistic [*Press et al.*, 1989], which has been previously used on hydrological records [e.g., *Marengo et al.*, 1995]. However, the Mann-Kendall statistic assumes that there is no serial correlation in the record for which the hypothesis of no trend is being tested [*WMO*, 1988]. This assumption is reasonable for rainfall records and is likely reasonable for many runoff records; it should be determined where substantial over-year storage may exist.

Tables 1 and 2 present the mean river discharge and rainfall records, respectively, in addition to the results of the Mann-Kendall statistic.

3. Variability and Change of River Records

3.1. Amazonia (Including Tocantins River)

The historical records of some rivers are shown in Figures 2a-2f, for Amazonia, eastern Brazil, and northwestern Peru. For Amazonia the Mann-Kendall test (Figure 3) indicates that there are no significant trends in the Negro, Jamari, Curua-

Table 1. Gauge Sites Used to Test for Trends in Mean Discharge During 3 Months of Highest Flow: Record Lengths (years), Mean Flow ($m^3\ s^{-1}$), Coefficients of Variation, Mann-Kendall Statistics for Trends, and Trend Significance

River/Station	Record Years	Mean	CV	Mann-Kendall Statistic	Trend
Parnaíba/Boa Esperança	65	658.1	0.26	+0.166	*
Parnaíba/R. Gonçalves	29	369.5	0.28	+0.156	NS
São Francisco/Juazeiro	64	4330.3	0.37	−0.277	**
São Francisco/Sobradinho	65	4781.6	0.32	+0.038	NS
Chira/Sullana	67	264.3	0.82	−0.150	*
Chira/Ciruelo	34	191.8	0.80	+0.004	NS
La Leche/Puchaca	85	11.5	0.64	−0.193	**
Zaña/El Batán	80	10.0	0.09	−0.172	*
Jequetepeque/Ventanillas	72	67.4	0.55	−0.162	*
Chicama/Salinar	85	140.3	0.40	−0.202	**
Moche/Quirihuac	79	24.2	0.59	−0.129	NS
Viru/Huacapongo	69	11.8	1.08	−0.135	NS
Coaracy Nunes/Araguari	65	1771.7	0.20	+0.005	NS
Uatumã/Balbina	65	360.9	0.50	−0.006	NS
Negro/Manaus	90	2716.5	0.04	+0.067	NS
Samuel/Jamari	65	694.9	0.13	−0.001	NS
Curua-Una/Curua-Una	65	310.6	0.32	+0.085	NS
Belmonte/Xingú	65	2037.5	0.22	+0.001	NS
Tucuruí/Tocantins	65	20986.5	0.43	+0.125	NS
Tucuruí/Maraba	22	19945.8	0.40	+0.119	NS

NS, no significant trend; one or two asterisks, trends significant at 5 and 1% levels. Increasing or decreasing trends are indicated by (plus) or (minus) signs where significant. Location of stations is indicated in the first row by capital letters, as displayed in Figure 1.

Table 2. Rain Gauge Sites Used to Test for Trends in Mean Daily Discharge in 3 Months of Highest Rainfall in Northeastern Brazil: Record Lengths (years), Mean Rainfall (mm), Coefficients of Variation, Mann-Kendall Statistics for Trends, and Trend Significance

Station	Record Years	Mean	CV	Mann-Kendall Statistic	Trend
Aracaju	70	207.7	0.46	+0.071	NS
Aracati	70	198.4	0.51	+0.046	NS
Areia Branca	80	138.3	0.06	+ 1.147	NS
Caicó	78	139.2	0.05	+0.157	*
Crateús	79	101.6	0.45	+0.087	NS
Campina Grande	75	150.0	0.36	+0.101	NS
Fortaleza	141	280.3	0.35	−0.004	NS
Icó	93	159.1	0.38	−0.017	NS
Iguatu	78	182.0	0.38	+0.094	NS
Pombal	78	141.7	0.45	+0.133	NS
Recife (Curado)	114	278.3	0.35	+0.238	**
Qixeramobim	95	150.7	0.45	+0.117	NS
Senador Pompeu	75	114.0	0.46	+0.016	NS
Souza Melo	72	159.1	0.43	−0.003	NS
Santa Quitéria	77	179.9	0.50	+0.043	NS
Uruquê	72	147.0	0.53	+0.068	NS

Una, Xingú, and Tocantins Rivers (the last four rivers flow from south to north, while the Negro River flows from north to south). These rivers exhibit positive Mann-Kendall statistics, but they do not reach statistical significance at the 95% level. Previous studies by *Marengo* [1995] have shown no unidirectional trends for the Rio Negro water levels at Manaus. Further analysis (not shown here) of the discharge series at the Uatuma, Jamari, Araguari, Curua-Una, and Xingú Rivers also indicate the absence of unidirectional trends. The variability of the discharge records is consistent with previous studies of river basins, which extend into the northwestern side of the Amazonia, such as the Negro and Manacapuru Rivers, and do not show any systematic increase or decrease in their records [*Marengo*, 1992, 1995; *Richey et al.*, 1989]. Consistent with the variability of river records, significant trends are absent in rainfall series on the basin of Rio Negro (Figure 4). These results, however, contradict those of *Dias de Paiva and Clarke* [1995], who found negative rainfall trends in this region by using shorter rainfall records. In this region the possible impact of deforestation and land use changes are not consistent with the long Negro River time series.

The discharge registered at the Araguari River at Coaracy

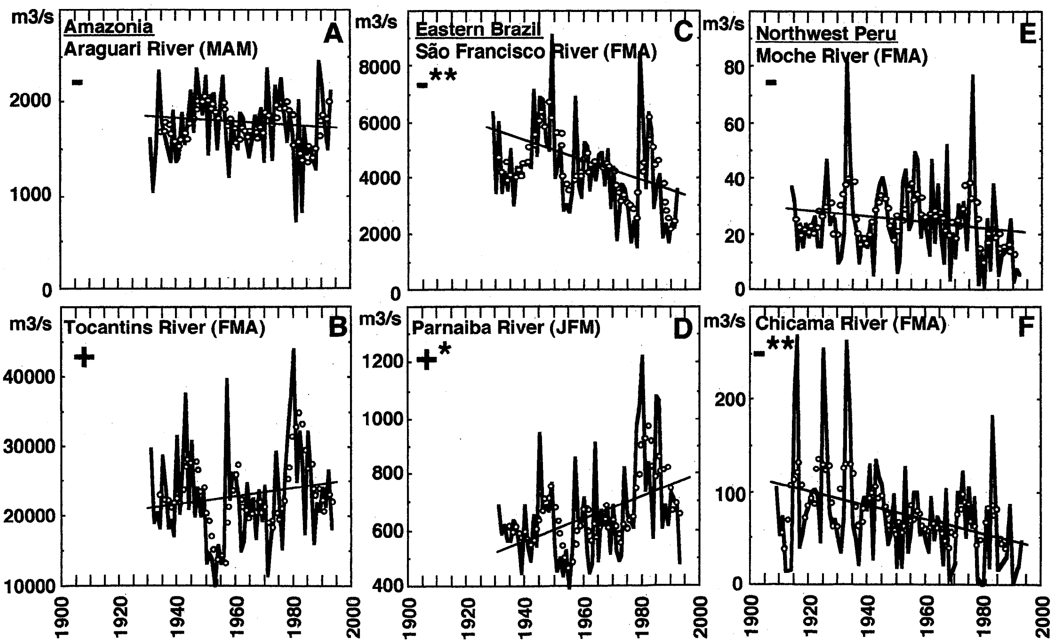

Figure 2. River discharge (m^3 s^{-1}) in 3 months with largest flows; the figures show in which months these flows occur. (a) Araguari River at Coaracy-Nunez (MAM). (b) Tocantins River at Tucurui (FMA). (c) São Francisco River at Juazeiro (FMA). (d) Parnaíba River at Boa Esperança (JFM). (e) Moche River at Quirihuac (FMA). (f) Chicama River at Salinar (FMA). Convention for statistical significance and sign as in Table 1. Lines show linear regression.

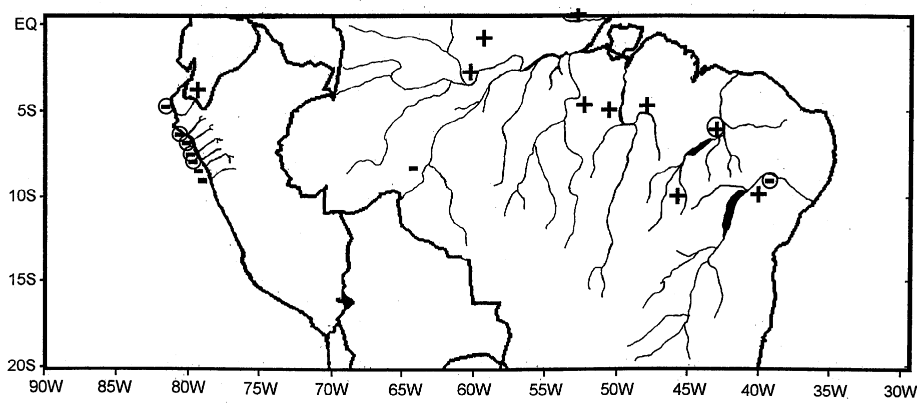

Figure 3. River gauging stations (compare Table 1) showing significant trends in mean discharge ($m^3 s^{-1}$) in 3 months of highest flow. Signs show increasing (plus) or decreasing (minus) trend; circles show trend significance at 5% levels or less.

Nunes reflects the interannual changes associated with the extremes of the Southern Oscillation, and especially the strong El Niño events of 1982–1983 and 1992 (Figure 2a). In all the river series, there are periods of above-average discharge from 1945 to 1960 and from the early 1970s to the early 1980s. Rivers with basins extending into southeastern Amazonia show a variation that is slightly different from that of the other Amazonian rivers, mainly due to the difference in rainfall mechanisms over their basins [*Marengo*, 1992]. Interannual variability of precipitation on the Rio Negro basin is large, as revealed by the river streamflow records, and is primarily associated with El Niño events [*Marengo*, 1995]. The Tocantins River basin is not part of the Amazon Basin because this river flows directly to the Atlantic. Its time series do not show any significant trend, and it does not appear to be associated with extremes in the Southern Oscillation. Alternating wet and dry periods are observed in the time series, and especially noteworthy are the dry period of 1945–1955 and the wet period of 1980–1990, which are not observed in the rest of Amazonia.

It can be concluded that there is not a trend toward dry or wet conditions in southern Amazonia, from the analysis of the three rivers with tributaries extending into southern Amazonia (Xingú and Tocantins), which represent rainfall conditions in that region. Periods of low SO phase, indicative of El Niño, are accompanied by relatively lower discharges in the northern basin (Figure 2a), which is not observed in the river records from the southern basin. However, the Southern Oscillation explains less than 40% of the variance in rainfall in northern Amazonia [*Marengo*, 1992].

3.2. Eastern Brazil

The records of São Francisco River at Juazeiro show a systematic decrease since the early 1970s [*Marengo*, 1995], which is indicative of drier conditions (Figure 2c). In contrast, the observations from the Parnaíba River at Boa Esperança display a tendency for increasing discharges especially during the last 25 years of record (Figures 2c and 5b). Even though the evidence shows statistically significant opposite trends in both adjacent basins, it is somewhat difficult to conclude that a climatic change may be occurring in eastern Brazil, with opposite tendencies in such a relatively small region of the world.

A careful analysis of the river series of the Parnaíba River at Boa Esperança indicates that the possible upward trend was driven by anomalously high discharges starting in the middle to late 1970s and ending in the middle 1980s. Discharge data for Parnaíba River at Ribeiro Gonçalves shows the same tendency and the same peaks as at Boa Esperança (Figure 5c). The order of magnitude of the discharges at Ribeiro Gonçalves is lesser than that at Boa Esperança, because of the influence of the Rio das Balsas, just before the entrance to the Boa Esperança Dam.

A comparison was made between the discharge of the São

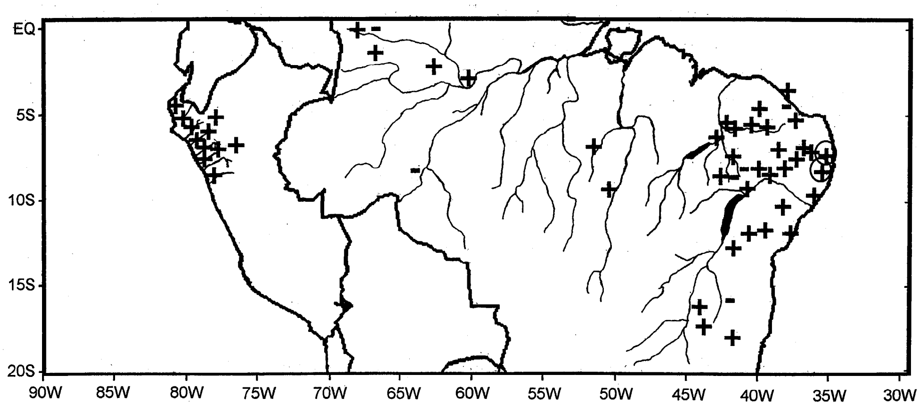

Figure 4. Rain gauge showing significant trends in mean rainfall (mm) in 3 months of highest flow. Signs show increasing (plus) or decreasing (minus) trend; circles show trend significance at 5% levels or less.

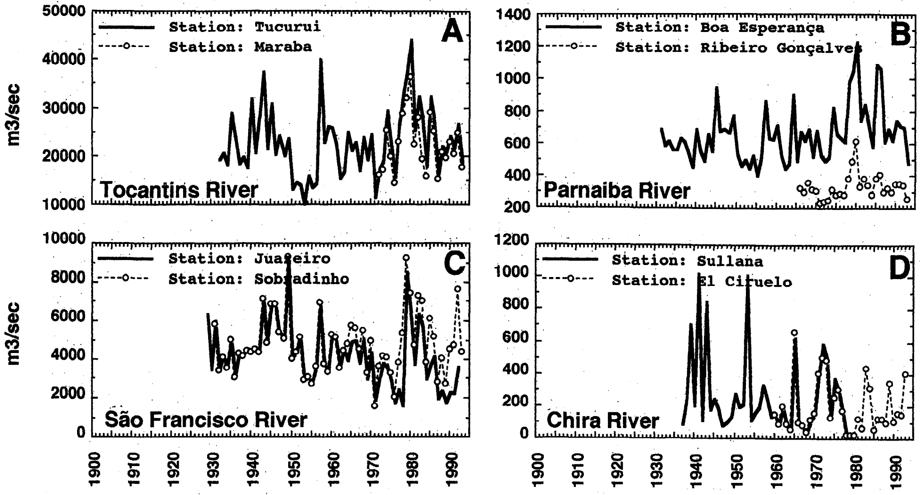

Figure 5. Time series of mean daily discharges ($m^3\ s^{-1}$) in 3 months of highest flow in fours rivers: (a) Tocantins, (b) Parnaíba, (c) São Francisco, and (d) Chira at each of two gauging sites.

Francisco River at Juazeiro and at the nearby gauging site of Sobradinho, 40 km to the west of Juazeiro, near the Sobradinho Dam. The river records at the Sobradinho site for the same season do not show any significant tendency toward dry conditions as indicated by the Juazeiro records, which agrees with the rainfall series at the basin. These new results update the findings from *Marengo* [1995] regarding the quality of the São Francisco River series at Juazeiro. Before 1960 the series were almost identical, while after 1962, the series at Juazeiro shows a gradual decrease, even though the variance remains similar to that at Sobradinho. The decrease in discharges after 1965 seems to be responsible for the negative artificial trend of the series at Juazeiro.

The observed tendency toward drier conditions seen in the Juazeiro records is likely due to extensive agricultural irrigation near Sobradinho, or from hydroelectric generation on the São Francisco River after Sobradinho [*Instituto Brasileiro de Geografia e Estadistica* (IBGE), 1985]. The Sobradinho turbine began to operate in 1979, which is approximately the time when the discharges at Juazeiro display a gradual reduction when compared to those in Sobradinho, making the Juazeiro series unsuitable for studying climate trends.

Rainfall in northeastern Brazil apparently does not show any trends toward drier or wetter conditions from the beginning of the century (Table 2, Figure 6a-6f). However, Recife-Curado (Figure 6b) exhibits a steady increase in the precipitation since the beginning of the century, with a rate of more than 200 mm/100 yr. After comparing this time series with the records of neighboring stations, it was concluded that the data at Recife cannot be considered homogeneous and probably has been affected by instrumentation problems. Similar conclusions can be drawn for the rainfall records at Caico (Figure 6d). Rainfall at other sites do not show any significant trends (Figures 6a, 6b, 6c, 6e, 6f, and Figure 4).

Although the record for Recife-Curado and Caico are the only ones to show a statistically significant trend, it will be noted that 17 of the 21 records show increases, while only 4 show decreases (Figure 4). If increases and decreases were

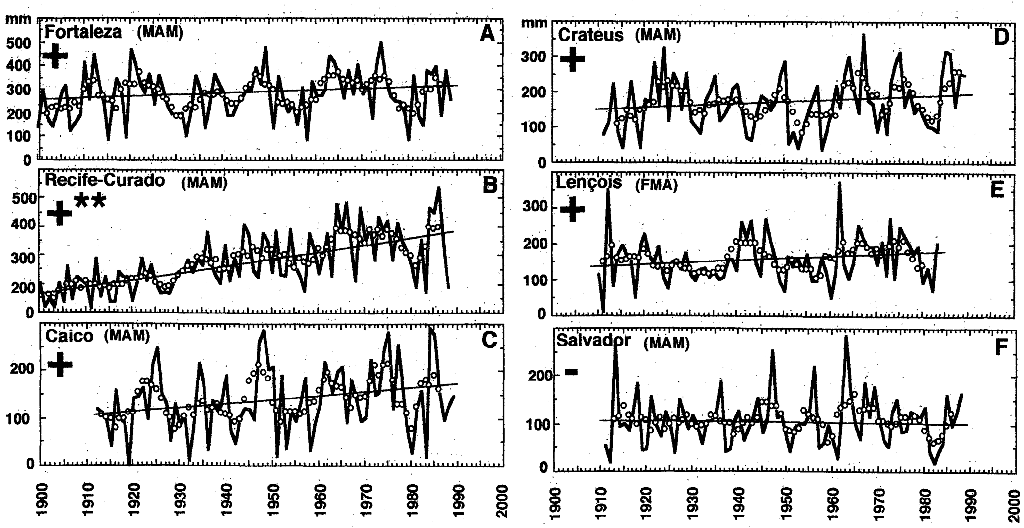

Figure 6. Mean rainfall in 3 months with largest values; the figures show in which months these flows occur. (a) Fortaleza (MAM). (b) Recife Curado (MAM). (c) Caico (MAM). (d) Crateus (MAM). (e) Lencois (FMA). (f) Salvador (MAM). Lines show linear regression.

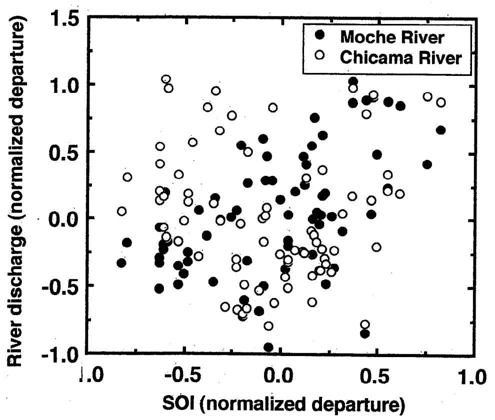

Figure 7. Scatter diagram of the relation between the Southern Oscillation Index (SOI) for January to February and the peak river discharge for the Moche (solid circle) and the Chicama Rivers (open circle). Values are expressed at normalized departures from the 1911 to 1990 mean. The SOI was defined as the pressure difference Tahiti minus Darwin.

equally probable, the expected frequencies of increases and decreases would both be 10.5, but the observed frequencies show significant departures from these expected frequencies ($\chi^2 = 8.048$ on 1 df: $P < 0.01$). The conclusion is not changed appreciably by omitting the record for Recife-Curado ($\chi^2 = 7.2$ on 1 df: $P < 0.01$). There is therefore some evidence of a small regional increase in rainfall during the three wettest months in northeast of Brazil.

3.3. Northern Coast of Peru

Marengo [1995] has found trends toward drier conditions in the basins of the Chira and Chicama Rivers in the northern coast of Peru. With the availability of more river data in the same region, new results from the analysis of discharge series of the La Leche, Zaña, Jequetepeque, Moche, and Viru Rivers located in the same region (Table 1, Figure 3) also exhibit this tendency toward drier conditions. The Mann-Kendall test (Table 1) indicates the presence of negative trends, from the Chira to the Viru River basins, which are statistically significant at the 5 or 1% level for most cases. Several important cities are located in this region, and the intense agricultural and industrial activity in those cities depends on the volume of water available from these rivers. If this apparent trend toward a desertification is real, then this could have a negative impact on local industries which in turn will affect human society in the region and nationwide.

It is observed in Figure 2e-2f and Figure 3 that most of these rivers shows anomalously large discharges associated with the occurrences of El Niño (e.g., 1925, 1936, 1976, and 1983) with several values reaching more than 300% of normal. The impacts of El Niño are felt strongly in the northwestern coast of Peru, where the SO index explains less than 50% of the variance of river discharge. It is noted that before 1945, episodes of anomalously high river discharges were more frequent, especially at the Moche and Chicama (Figures 2e-2f) and others (Zaña, Chira, and Viru Rivers). In this regard, *Quinn* [1991] and *Quinn et al.* [1987] indicated that between 1900 and 1945, 16 El Niño events were reported, with 6 events classified as strong or very strong (very strong events in 1925–1926, 1940–1941). Very high river discharges in the northwestern coast of Peru before 1945 generally correspond to events ranging from moderate to very strong. Between 1945 and 1992, 10 El Niño events were reported, with 2 being strong, one very strong (1982–1983), and 7 moderate. The high river discharges in 1983 and 1987 correspond to strong events, while the high discharge in 1951 corresponds to a moderate event. Based on the river discharge records in the northwestern coast of Peru and the association between El Niño events and anomalously high discharges, we note that before 1945, episodes of anomalously high river discharges occurred with higher frequency than after 1945. However, this does not imply that strong El Niño were more frequent before 1945.

The records of the Moche and Viru Rivers indicate that some episodes of high river discharges are coincident with El Niño years but perhaps to a lesser degree than the northernmost rivers. Thus Figure 7 shows a scatter diagram of normalized departures of the January-February SOI and the normalized river discharges for the Moche and Chicama. It is proposed that El Niño conditions do not necessarily imply high river discharges in all rivers in the northern coast of Peru. From Figure 2f the Chicama River shows some extremely high values during the low SO phase, while the Moche River shows the opposite pattern with high river discharges during the high SO phase (La Niña-like conditions). This could be explained in terms of (1) the orientation of the basin and (2) the rainfall distribution in the basin. In the lower basin near to the coast the El Niño events are accompanied by heavy rains, while in the upper basin this is not necessarily true, depending on the orientation of the basin and how much it extends into the Andes. We have to point out that the relative contribution of rain from the upper basin to the discharge of the rivers is higher than the contribution of rain in the lower basin. As a consequence, we have mixed associations between river discharges and El Niño in some basins of the northwestern coast of Peru.

The observed negative trends in the river records in northern Peru would be reason to worry if they were real. Unfortunately, a complete dense rainfall network in many of these basins is not available. Few stations have complete records, and these stations are primarily located along the coast, so it is very difficult to infer if there is a systematic reduction in the rainfall over the upper and middle basins, which in turn would produce the negative river trends.

For Chira River, river records are available at the sites in Sullana and El Ciruelo (Table 1), the latter has a shorter series than the former. The registers at Sullana exhibit negative trends, while those from El Ciruelo do not, and since the reservoir was built in between these two sites, there is a possibility that the negative trends at Sullana may be a consequence of water management and regulation for use in irrigation in the lower part of the Chira Valley since the early 1980s. Figure 5d displays the discharges of the Chira River at both Sullana and El Ciruelo sites. During the 1959–1978 the records are almost identical before 1970, while after that, the peaks at El Ciruelo are comparably smaller than those at Sullana.

Another possibility is that the extreme high peaks during 1938, 1940, 1952, and 1954 are driving the Sullana records toward dry conditions, which is not seen in the El Ciruelo record since its data does not extend before 1960. A similar trend analysis of the Sullana data, removing the 4 above mentioned peaks, indicates no significant trends in either direction.

At the Jequetepeque River the presence of the Gallito Ciego reservoir may explain the negative trends due to an intensive use of water for irrigation purposes. On the other hand, the La

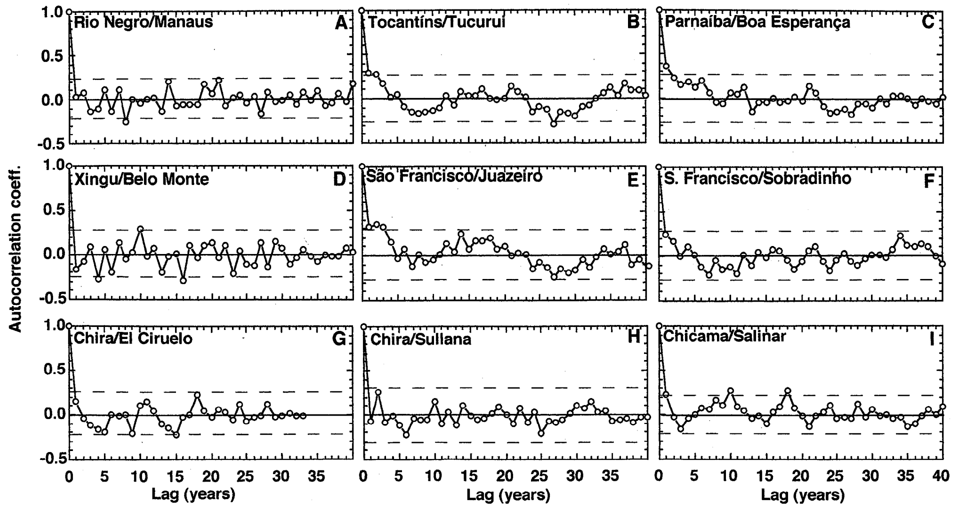

Figure 8. Correlograms for time series of mean daily discharge (m^3 s^{-1}) in 3 months of highest flow in selected rivers: (a) Rio Negro at Manaus, (b) Tocantins at TucuruI, (c) Parnaíba at Boa Esperança, (d) Xingú at Belomonte, (e) São Francisco at Juazeiro, (f) São Francisco at Sobradinho, (g) Chira at El Ciruelo, (h) Chira at Sullana, (i) Chicama at Salinar. Dashed lines show 95% confidence limits on hypothesis of no serial correlation.

Leche, Zaña, and Chicama do not have any reservoirs or dams that would produce such disturbance in the river records near the coast. In these rivers the tendency toward negative trends still persists after removing extremely high peak values before 1935, as it was done with the Chira River. However, without detailed rainfall information on the upper and middle basin of these rivers, or any other data from the tributaries of these rivers, it will be difficult to prove whether the negative trends are real.

4. Are River Trends and Thus the Regional Climate Change Real?

In this section, we discuss whether the "climatic trends" found from the analyses of the São Francisco and Parnaíba Rivers as well as those in the river records from the northern coast of Peru are real, or if in fact due to nonclimatic effects (regulation of the water volume by dams, intensive water for local agriculture, or generation of hydroelectric energy, water storage, and a possible serial correlation).

The Mann-Kendall test has been applied for detecting trends in river/rainfall data as an indication of a possible climatic change. This test assumes that the correlation between annual discharges is very low. In some basins, however, there are other factors that can make this assumption unrealistic, restricting the applicability of the test.

Every large drainage basin, such as the Amazon, can show a large serial correlation violating the basic assumption of the Mann-Kendall test. Because of the enormous storage capacity within those basins, streamflow and water level records have a long memory (basin-memory effect) which increases the serial correlation. Another hypothesis raised by *Hodnett et al.* [1996] is based on the Anglo-Brazilian Amazon Climate Observation Study (ABRACOS) soil storage observation in Maraba. The record showed that a strong dry season could affect the soil water replenishment in the subsequent dry season. Since streamflow generation in tropical basins is dominated by base flow, a prolonged dry season might affect the groundwater discharge to the river in the next year. In Manaus, where the dry season is mild, this effect may be negligible.

For northeastern Brazil rainfall, there are significantly more positive Mann-Kendall statistic values than would be expected by chance, on the hypothesis of no regional trend. There is evidence of a positive trend in rainfall, at least in the three wettest months. This may have wider implications for the politics of the drought industry of northeastern Brazil, if there is a slow region-wide increase in rainfall over long periods (even if the increase is in terms of millimeters). Further analysis is required to explain how this occurs: whether, for example, individual rainfall events are becoming more intense in the wettest months, or whether rainfall in the remaining nine months is diminishing, whether the time intervals between rainfall events is changing, or whether any of the many other possible hypotheses is supported. These results, which will be reported in a later paper, require an analysis of daily rainfall records.

It is important to note that trends in mean wet-season streamflow can be explained by man-made influences. Increases in storage or increased water loss for irrigation can explain observed trends, and a possible large serial correlation in those cases may also affect the Mann-Kendall test. However, rainfall series generally show very low correlation, and do not affect the Mann-Kendall test. Therefore the test applied to rainfall data can confirm or contradict the test results obtained on river series.

Coefficients of autocorrelation were calculated for several river discharge records: the Negro River at Manaus, the Tocantins River at Tucuriu, the Parnaíba River at Boa Esperança, the Xingú River at Belo Monte, the São Francisco River at Juazeiro and Sobradinho, the Chira River at Ciruelo and Sullana, the Chicama River at Salinar (Figure 8a-8i). Of these series, Manaus, Sobradinho, Xingú, and Chira series do not display trends, and even though they have very large basins, the correlation of streamflow/levels between two consecutive years is very low, making the Mann-Kendall a suitable test. The Parnaíba shows a positive trend significant at 5% level; however, the autocorrelogram indicates that the year-to-year correlation is very large. The same test was applied to rainfall in the upper and middle sections of the basin of the Parnaíba and displays no trends in the rainfall records. For the rivers in the northwestern coast of Peru the presence of negative trends, significant at the 1% level, is not supported by the similar trends in the rainfall regime either. For the Chicama River at Salinar (Figure 8i) there is a very large correlation between streamflow for consecutive years. For other rivers in this region the year-to-year correlation is weak, and the Mann-Kendall test would indicate that the statistically significant trends found for some of the rivers in the region are real, but there is not sufficient rainfall data to confirm these results.

It should be noted that the autocorrelation function is applied to a stationary stochastic process. If the time series display a significant trend, it can be argued that the series is no longer stationary. However, we are using correlograms to check the theoretical assumptions of the Mann-Kendall test and not to extract a conclusion of the behavior of the stochastic process.

5. Conclusions

An analysis of long hydrological records and complementary rainfall data are presented for Brazil, Amazonia, and northwestern Peru. River and rainfall records in Amazonia do not show any significant trends toward drier or wetter conditions. However, on interannual scales they display periods that may be described as dry or wet, which is characteristic of the natural climate variability in the region. The interannual variability of climate in Amazonia is linked with El Niño, with droughts occurring during extreme warm events.

In eastern Brazil, there is evidence suggesting that negative trends found in the São Francisco River at Juazeiro are not explained by the rainfall variation at its upper and middle basin, and river records at the nearby Sobradinho site do not show any trend. Thus the negative trend at Juazeiro is likely a consequence of water management rather than a climate change. For the Parnaíba River the significant upward trends are consistent with the rainfall records in its middle basin. However, these upward trends are related to extremely large rainfall events between 1980 and 1985.

Alternating drier and wetter periods have been detected in both the Parnaíba and the São Francisco Rivers as well in rain in northeastern Brazil, with some lasting more than 10 years. In addition, we found evidence that supports a slow region-wide long-term increase in rainfall in northeastern Brazil.

The significant negative trends in the river records of the northwest coast of Peru is more difficult to explain, because long rainfall records are not available in this region for complementary analysis. Some rivers exhibit negative trends due to water management rather than to climate-induced changes, while others show extremely high values at the beginning of the record, producing unrealistic negative trends. The data at Chicama and La Leche show significant negative trends even after removing anomalously high values at the beginning of the series.

It is difficult to distinguish climate-induced trends that may exist in the river data series from man-made effects. However, from our analysis the latter seems to be the explanation for observed significant trends in eastern Brazil and the northern coast of Peru. In the Amazon Basin as well as in northeastern Brazil, hydrological conditions do not reflect any trend in either direction, while they reflect drier or wetter periods at decadal timescales. In the smaller river basins near the coast of Peru, some trends are explained by human activities and water use for irrigation; however, in the larger basin of the São Francisco River the negative trends are related to water use for power generation.

With regard to the Mann-Kendall test, it has been shown that this test may not be suitable for regions under intensive water use and management or on rivers with a large basin-memory. At least it should not be applied to river data solely in a basin. If the null hypothesis in the Mann-Kendall test is rejected, there are two possible interpretations: (1) there is a trend and (2) there is a failure in the null hypothesis, such as the assumption of no serial correlation. In cases where there is a substantial serial correlation, it seems incorrect to conclude that interpretation 1 is the explanation. One way to solve this problem is to apply this test also to rainfall records in the upper and middle basins to confirm the trends shown by the river data. In the end, it will still be difficult to explain a trend in rain and streamflow as due to a regional climate change.

In summary, it appears that the hydrology in tropical South America does not show any tendency toward dry or wet conditions since the beginning of the century. However, in the northwestern coast of Peru the variability on interannual scales shows that some years have been extremely dry or wet in the region, and extreme wet events in this region were more frequent and intense before 1945. Although river discharges show limitations in determining the direction of global climate change due to the reasons outlined in section 3.3, they are very important in integrating the change induced not only by global climate change but also by regional human activities. Since flows are important for the ecology functioning of dry land and wetland ecosystems, river flow changes will have feedbacks with the atmosphere by altering the radiative forcing in the flood plains.

Acknowledgments. The authors wish to thank Robin T. Clarke, from the Universidade Federal do Rio Grande do Sul, Brazil, and Uma Bhatt from COLA for reading and making comments on the manuscript. Sources of data were INRENA, ELETROBRAS, ELETRONORTE, Lawrence Greischar from University of Wisconsin-Madison, and Guillermo Obregón from INPE, Brazil. José Marengo and Javier Tomasella were sponsored by the Brazilian National Research Council (CPNq)-RHAE Program at the CPTEC in São Paulo, Brazil. Cintia Uvo is on leave from CPTEC and under a fellowship of the Swedish Institute at the Department of Water Resources Engineering at Lund University. River data were kindly provided by Instituto Nacional de Recursos Naturales (INRENA, 1994), Servicio Nacional de Meteorologia e Hidrologia, Centrais Elétricas Brasileiras S.A., Centrais Elètricas do Norte do Brasil S.A., the Centro de Previsão de Tempo e Estudos Climáticos, the Departamento Nacional de Aguas e Energia Elétrica, and the Divisão de Hidrologia of the State of Piauí. Rainfall data were obtained from the archives of CPTEC, the Carbon Dioxide Information Analysis Center (*R. Vose et al.*, 1992) at Oak Ridge National Laboratory, and the Climate Research Unit of the University of East Anglia, U.K.

References

Box, G. E., G. Jenkins, and D. W. Bacon, Models for forecasting seasonal and nonseasonal time series, in *Proceedings of the Advanced Seminar on Spectral Analysis of Time Series*, edited by B. Harris, pp. 271–311, John Wiley, New York, 1968.

Bruinjzeel, L. A., Predicting the hydrological impacts of land cover transformation in the humid tropics: The need for integrated research, in *Amazonian Deforestation and Climate*, edited by J. Gash,

C. Nobre, J. Roberts, and R. Victoria, pp. 15–56, John Wiley, New York, 1996.

Chiew, F., and T. McMahon, Detection of trend or change in annual flow of Australian rivers, *Int. J. Climatol.*, *13*, 643–653, 1993.

Chu, P.-S, Z.-P. Y., 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.

Dias de Pailva, E. M. C, and R. T. Clarke, Time trends in rainfall records in Amazónia, *Bull. Am. Meteorol. Soc.*, *75*, 579–583, 1995.

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

Gentry, A., and J. Lopez-Parodi, Deforestation and increased flooding in the upper-Amazon (replay to Nordin and Meade), *Science*, *215*, 427, 1982.

Hastenrath, S., and L. Greischar, Further work of Northeast Brazil rainfall anomalies, *J. Clim.*, *6*, 743–758, 1993.

Hodnett, M., M. Oyama, J. Tomasella, and A. Marques Filho, Comparisons of long-term soil water storage behaviour under pasture and forest in three areas of Amazonia, in *Amazonian Deforestation and Climate*, edited by J. Gash, C. Nobre, J. Roberts, and R. Victoria, pp. 57–78, 1996.

Instituto Brasileiro de Geografia e Estadistica, (IBGE), *Atlas Nacional do Brasil, Região Nordeste, Secretaria de Planejamento da PresidÍncia da República*, Fundacão, IBGE, 1985.

Instituto Nacional de Recursos Naturales (INRENA), *Descargas de los Rios y Almacenamiento de Reservorios y Represas de la Costa Peruana*, 80 pp., Minist. de Agric., Lima, 1994.

Lettenmaier, D., E. Wood, and J. Wallis, Hydro-climatological trends in the continental United States, 1948–88, *J. Clim.*, *7*, 586–607, 1994.

Marengo, J., Interannual variability of surface climate in the Amazon Basin, *Int. J. Climatol.*, *12*, 853–863, 1992.

Marengo, J., Variations and change in South American streamflow, *Clim. Change*, *31*, 99–117, 1995.

Press, W., B. Flannery, S. Teukolsky, and W. Vetterling, *Numerical Recipes, The Arts of Scientific Computing Fortran version*, 702 pp., Cambridge University Press, New York, 1989.

Quinn, W., A study of the Southern Oscillation-related climatic activity for A.D. 622–1990 incorporating Nile River flood data, in *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*., pp. 119–150, edited by H. Diaz and V. Markgraf, Cambridge University Press, New York, 1991.

Quinn, W., V. Neal, and S. Antúnez de Mayolo, El Niño occurrences over the past four and a half centuries, *J. Geophys Res.*, *92*, 14,449–14,461, 1987.

Richey, J., C. Nobre, and C. Deser, Amazon River discharge and climate variability: 1903 to 1985, *Science*, *246*, 101–103, 1989.

Rocha, H., C. Nobre, and M. Barros, Variabilidade natural de longo plazo no ciclo hydrologico da Amazónia, *Climanalise*, *4*(12), 36–42, 1989.

World Meteorological Organization (WMO), Analyzing long time series of hydrological data with respect to climate variability, *WCAP-3, WMO/TD-224*, Geneva, 1988.

J. A. Marengo and Javier Tomasella, Centro de Previsão de Tempo e Estudos Climáticos, CPTEC. INPE, 12630-000 Cachoeira Paulista, São Paulo, Brazil. (e-mail: marengo@cptec.inpe.br)

C. R. Uvo, Department of Water Resources Engineering. Lund University, Box 118, S-221 00 Lund, Sweden.

(Received December 11, 1996; revised September 8, 1997; accepted September 9, 1997.)