A Recent Increasing Trend in the Streamflow of Rivers in Southeastern South America

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ABSTRACT

This paper examines the records of streamflow during the period 1901–95 corresponding to four major rivers in southeastern South America: Uruguay, Negro, Paraná, and Paraguay. The emphasis is on the detection of long-term trends in the records. The authors demonstrate that the 30-yr running averaged streamflows increased after the mid-1960s at a rate that is approximately linear but not the same in all rivers. There seems to be a tendency toward leveling off in the most recent values. The increased streamflow is consistent with a significant decrease in the amplitude of the seasonal cycle in all rivers, except in the Negro River. An analysis of the sea surface temperature in the eastern equatorial Pacific Ocean suggests that an important component of such an increase in streamflows is consistent with a large-scale and low-frequency variability of the climate system.

1. Introduction

The time series of streamflow estimates in major rivers around the world can be even centuries long. The reason for such a close monitoring of an environmental parameter is that a better understanding of river behavior is a key factor in the design and operation of hydroelectric plants. This understanding includes the streamflow sensitivity to climate anomalies, which involves complex interactions between atmospheric and land processes. In this context, streamflows appear as integrators of climate impacts in the corresponding river basins.

This paper examines the time series of streamflow in four major rivers of southeastern South America: Uruguay, Negro, Paraná, and Paraguay (see Fig. 1). Our interest is the existence of *long-term trends* in the records during the period 1901–95. García and Vargas (1997) inspected the variation of the streamflows in the Paraná, Paraguay, and Uruguay Rivers during the period 1901–92. They searched for years with significant changes in the tendency of the time series and found that one such change developed around 1970. Our study differs from García and Vargas (1997) in two principal aspects: 1) we do not target changes in tendency of the time series for particular years, since variations in river behavior typically develop over longer periods, and 2) our statistical analysis is not performed in the framework of Gaussian distributions, since it is apparent that raw streamflows do not satisfy this hypothesis. In addition, we examine the possible relationships between the behavior of the four rivers and that of another climate parameter such as the sea surface temperature (SST) in the eastern equatorial Pacific Ocean.

2. Datasets

a. River streamflows

Our dataset consists of the time series of monthly streamflow in the Uruguay, Negro, Paraná, and Paraguay Rivers. No significant contribution to the streamflow from snow melting is expected in these rivers. The requirement of long datasets ending in recent times excluded from our analysis the Salado River, which appears in Fig. 1 as joining the Paraná at about 32°N: the time series for Salado's largest basin ends in 1962. The area of the drainage basins, the name and location of the stations where the data were gathered, and the period covered by the data are shown in Table 1. The monitoring stations in Uruguay and Negro Rivers, as well as in the Paraná and Paraguay Rivers, are located upstream

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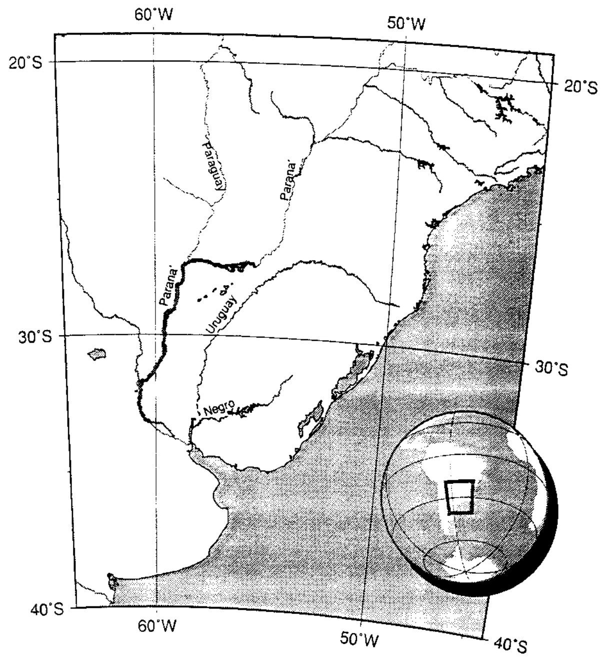

FIG. 1. Geographical location of the rivers selected for this study. The area of the drainage basins and the name and location of the stations where the data were gathered are given in Table 1.

of their respective junctions, and can thus be considered as fairly independent of each other.

Streamflows in the Paraná and Paraguay Rivers were measured at the same location and with the same method for the entire length of record. N. O. García, who provided the data for these rivers, also performed a quality control of the records (García and Vargas 1997). Dams were built in the Negro and Uruguay Rivers in 1939 and 1980, respectively. When dams are present in the rivers, the method used to estimate streamflows is based on a mass budget of the corresponding reservoirs, which includes a parameterization of surface evaporation. In our opinion the change in estimation procedure at a particular year does not affect the principal results of this study that focuses on much longer periods.

b. SST in the eastern equatorial Pacific

Our time series of this climate parameter is based on Wright's SST index (Wright 1989). This is the mean SST anomaly over the region: 6°–2°N, 170–90°W; 2°N–6°S, 180°–90°W; and 6°–10°S, 150°–110°W for the period from 1881 to 1986. We extended this time series until 1995 by using the correlations found by Simpson et al. (1993) between Wright's index and SST anomalies in El Niño 3, which we obtained from the National Oceanic and Atmospheric Administration–National Weather Service–National Centers for Environmental Prediction *Climate Diagnostics Bulletin.* The resulting time series will be referred to as the WIN3 index in this paper.

TABLE 1. Area of drainage basins, and names and locations of streamflow monitoring stations for the rivers considered in this study.

River	Drainage basin (km^2)	Station	Location	Data period
Paraná	975 375	Posadas	27°23′S, 56°53′W	Sep 1901 Aug 1994
Paraguay	1 100 000	Puerto Bermejo	27°20′S, 58°30′W	Sep 1910 Aug 1994
Uruguay	500 000	Salto Grande	31°S, 58°W	Jan 1909 Dec 1995
Negro	39 700	Rincón del Bonete	33°S, 56°W	Jan 1909 Dec 1995

3. The 30-yr averaged streamflows

We start by inspecting the 30-yr centered running averages of the annual streamflow in the rivers selected for this study. The length of averaging period was chosen in order to emphasize long-term trends and is consistent with standard hydrologic practice. Figure 2 shows those averages divided by the corresponding standard deviations of the time series, which were estimated from the entire period of record. In this way, corresponding values have comparable magnitudes despite the large differences in the rivers' size and typical discharge. The streamflow in all rivers shows a slight decreasing trend in the first two decades of the record and a tendency to level off in the period 1920–40. Figure 2 clearly supports the notion that all streamflows have increased almost monotonically since the early 1960s (see also Fig. 3 in Mechoso and Pérez 1992) and in the Negro River since the late 1940s. We fitted a linear growth as a function of time to the annual streamflows after 1965 and obtained the rates shown in Table 2. The values in Table 2 indicate that the increase did not proceed at exactly the same rate in all rivers.

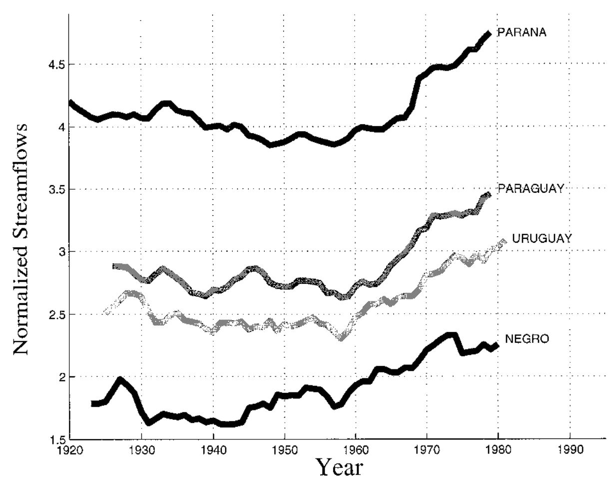

FIG. 2. 30-yr centered running averages of the annual streamflows divided by the corresponding standard deviations for the four rivers considered in this study. From top to bottom: Paraná (σ = 89.9 km^3 yr^{-1}), Paraguay (σ = 39.3 km^3 yr^{-1}), Uruguay (σ = 54.7 km^3 yr^{-1}), and Negro (σ = 8.6 km^3 yr^{-1}).

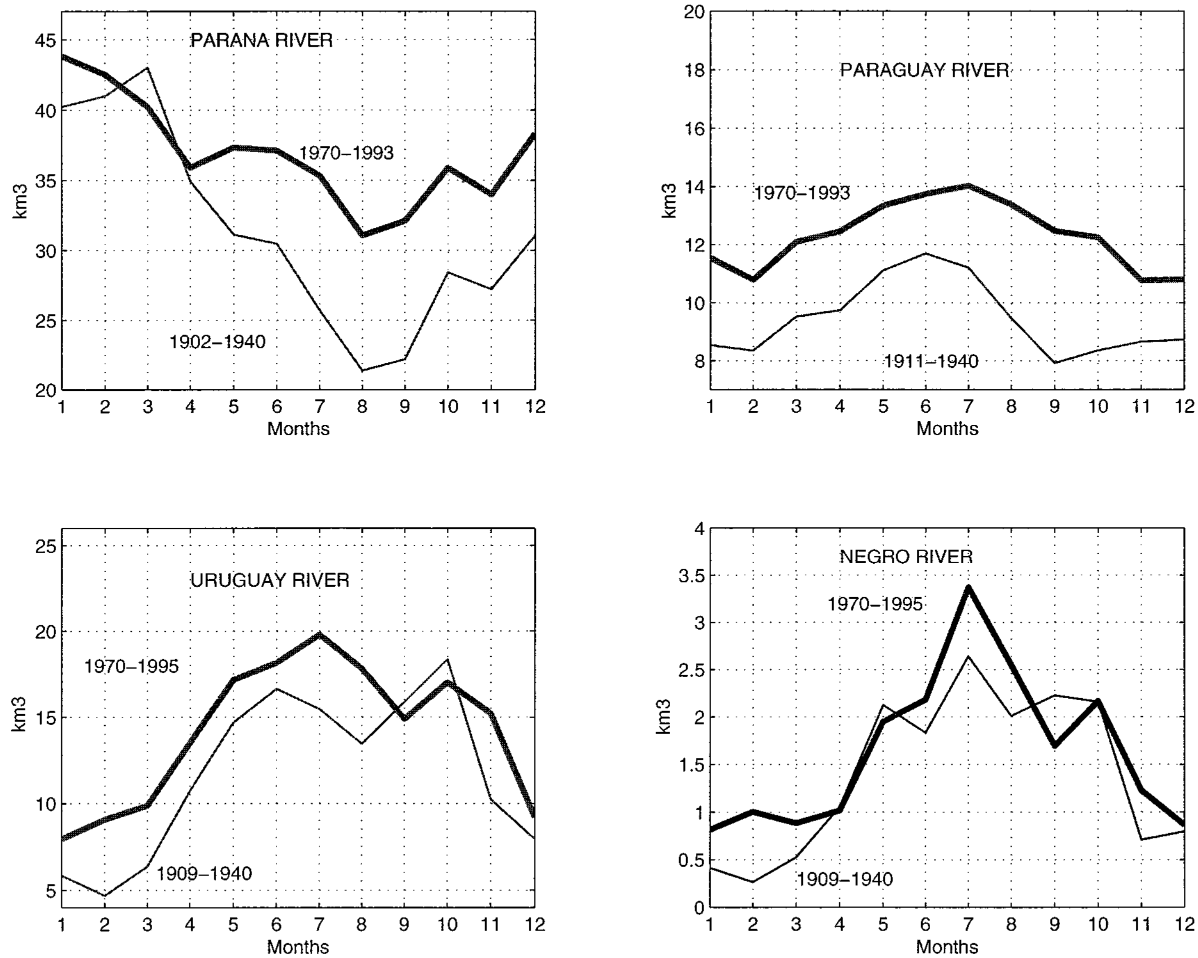

FIG. 3. Monthly streamflows averaged over period I (thin lines) and period II (thick lines) for the four rivers considered in this study: Paraná (upper left), Paraguay (upper right), Uruguay (lower left), and Negro (lower right).

These considerations suggest that the analysis of streamflow changes in time can be organized as a comparison between an ‘‘earlier’’ period (period I) and a ‘‘later’’ period (period II). Period I comprises the approximately 30-yr span from the beginning of the records until 1940. This period ends shortly before the long and importance droughts that developed in the river basins during 1943, 1944, and 1945, and that were extraordinarily strong anomalous climate events. Period II comprises the approximately 25-yr span from 1970 until the most recent records available to us at this time (1995). There is no particular reason for selecting 1970 as the beginning of this period, except for its separation from the anomalous drought and similarly anomalous floods that developed in Uruguay during the late 1950s.

TABLE 2. Linear growth rates after 1965 (per unit area of corresponding basin) of the curves shown in Fig. 2.

River	Paraná	Paraguay	Uruguay	Negro
10^6 (km^3 yr^{-1}) km^{-2}	5.12	2.82	3.20	2.19

To test the hypothesis that the distributions of annual streamflows in periods I and II have the same median against the alternative hypothesis that streamflows in the later period have a larger median than those in the early period, we apply the Wilcoxon test (see, e.g., Gibbons and Chakraborti 1992). There is no definite evidence that annual streamflows cannot be considered as independent of each other, except for long droughts such as those during the 1940s. Note that we do not consider the other possibility, namely that streamflows in period I have a larger median than those in period II, since there are clear indications that this is not the case. Table 3 shows the results obtained in the Wilcoxon test. All rivers show a very small probability that ‘‘the annual streamflows in the early and later periods have the same median’’ versus ‘‘the annual streamflows in the later period have a larger median than those in the earlier period.’’

To examine the change in the seasonal cycle of streamflow, we inspect the monthly streamflows in all rivers for periods I and II (see Fig. 3). For the Paraná

TABLE 3. Results of the Wilcoxon test for the probability that the streamflows in period I (before 1940) and period II (after 1970) have the same median versus the probability the streamflows in the later period have a larger median than those in the earlier period. Superscript asterisk (*) indicates nonsignificant values (larger than 5%).

River	Annual	February	July	November
Paraná	0.375	32.00*	0.02	0.06
Paraguay	0.120	0.30	2.00	4.40
Uruguay	4.720	0.01	9.72*	4.30
Negro	2.986	0.35	21.00*	1.70

River, the monthly streamflows in period II are larger than in period I, except during the first trimester of the year (southern summer). For the Paraguay River, values in period II are systematically larger than in period I. For the Uruguay and Negro Rivers, the streamflows in period II are larger than in period I during the southern summer and winter months. Table 3 shows that all results described for the Paraguay River are significant. For the Paraná River, the values corresponding to the southern summer are nonsignificant. For the Uruguay and Negro Rivers, on the other hand, the values corresponding to the southern winter are nonsignificant. The latter result highlights the importance of higher-frequency phenomena in the basins of the Uruguay and Negro Rivers during the southern winter months. It is also apparent that the amplitude of the annual cycle in period II tends to be smaller than in period I in all rivers, except in the Negro River.

4. Relationships with SST in the tropical Pacific Ocean

Figure 4 shows the 30-yr running averages of the WIN3 index and the corresponding grand-mean anomaly of the normalized streamflows in the four rivers selected for this study. The figure is consistent with a simultaneous increase in both mean streamflow and magnitude of SST anomalies in the eastern equatorial Pacific after the mid-1960s, and it suggests that all rivers experience a similar low-frequency behavior. The WIN3 index shows a tendency to decrease after the early 1980s. Since 1980 is the last element that can be obtained by taking the 30-yr running average of time series that end in recent times, we inspected the 10-yr running averages of the streamflows in all rivers. These records are also consistent with a tendency to decreasing values after the early 1980s.

Several authors have found close associations between river discharge in South America and the Southern Oscillation index (SOI) (e.g., Molion and Moraes 1987; Hastenrath 1990). The Uruguay and Negro Rivers drainage basins, as well as part of the Paraná River basin, belong to a region of South America whose climate anomalies in interannual timescales are significantly linked to those in the eastern equatorial Pacific. Ropelewski and Halpert (1987, 1989) and Pisciottano

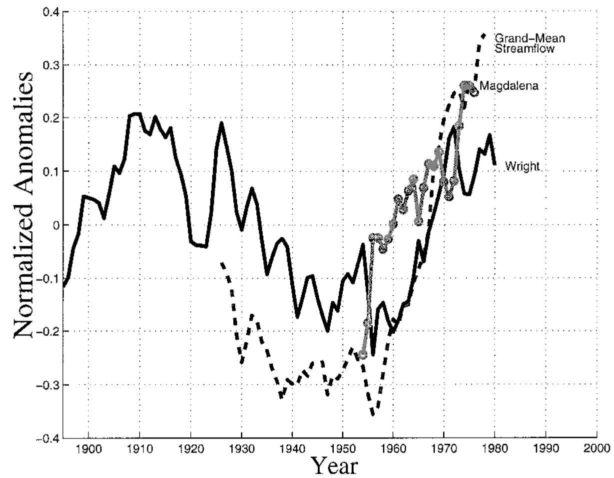

FIG. 4. As in Fig. 2 except for the grand-mean anomalies of the normalized streamflows in the four rivers in southeastern South America (Paraná mean = 385.6 km^3 yr^{-1}, Paraguay mean = 120.8 km^3 yr^{-1}, Uruguay mean = 145.5 km^3 yr^{-1}, and Negro mean = 17.4 km^3 yr^{-1}), and the Magdalena River (mean = 226.1 km^3 yr^{-1}, σ = 36.9 km^3 yr^{-1}), as well as the WIN3 index.

et al. (1994) demonstrated that rainfall in southeastern South America tends to be above the median during certain months of El Niño years and below the median during other months in years with a high value of the SOI (cold events in the equatorial Pacific Ocean, hereafter called HSOI events). Consistently, Mechoso and Pérez (1992) found that the streamflow in the Uruguay and Negro Rivers shows a clear tendency to be below the median during the period June–December in years with a high SOI, and a slight tendency to be above the mean during the period November–next February in El Niño years, with values that are occasionally well above the mean. Our results suggest that qualitatively similar relationships between climate anomalies in southeastern South America and the eastern equatorial Pacific are at work for long timescales.

One can wonder whether this similarity has a more general validity. We can provide one example against this notion by considering the time series of streamflows corresponding to the Magdalena River, which runs in Colombia (northwestern South America; Calamar Station at 10°N, 75°W; the surveyed area is 257 438 km^2). Figure 4 shows that the simultaneous increase in the 30-yr running averages of streamflow and magnitude of SST anomalies in the eastern equatorial Pacific also holds for this river. Nevertheless, Ropelewski and Halpert (1987, 1989) and Aceituno (1988) showed that precipitation tends to be below average during ENSO events and above average during HSOI events in a region that comprises the Magdalena River basin. Aceituno (1988) also showed that there are highly significant positive correlations between the Magdalena River discharge and the SOI. It appears, therefore, that the broadly inverse variations found between the rivers in southeastern South America and the Magdalena River in interannual timescales do not extend to longer timescales.

5. Conclusions

We have examined a long record of streamflow from four major rivers in southeastern South America: Uruguay, Negro, Paraná, and Paraguay. To emphasize longer than interannual timescales, we considered the 30-yr running average of the record. For the analysis, we applied statistical tests that use nonparametric methods.

The 30-yr running average of the streamflow shows that the median after 1970 is significantly larger than the medians for an approximately 30-yr-long period ending in 1940. Further, the record after the mid-1960s is consistent with a linear growth whose rate is not exactly the same for all rivers. The increased streamflow is consistent with a significant decrease in the amplitude of the seasonal cycle in all rivers, except in the Negro River. The *30-yr averaged* streamflow records closely follow an index representing the SST anomalies in the eastern equatorial Pacific. This index shows a minimum in the mid-1940s, when there was the strongest drought of this century in southeastern South America. These results suggest that the streamflow variations described in this paper are integral part of the large-scale variability of the climate system. The most recent records suggest a leveling off of the streamflow values.

In the context of long timescales we cannot ignore the impacts on river discharge of global climate change associated with anthropogenic effects. There is the possibility that the increase in streamflows is linked to greenhouse warming. This, however, is not supported by the lack of systematic trends in records for several rivers of South America by Marengo (1995). The principal economic activity in the large river basins of southeastern South America in this century has been cattle growing, whose techniques and demands on the soil have not changed significantly in the peiod covered by this study. We base this statement on the similarity in the ratios between mean streamflow and rainfall in the Negro River basin for periods I and II that we verified by inspection of the corresponding records. This suggests that soil conditions have not changed significantly in the Negro River basin. On the other hand, the different behavior of the pairs Paraná–Paraguay and Uruguay–Negro may be due, at least in part, to the differential effects of Amazonian deforestation. The results obtained by Nobre et al. (1991) using a version of the general circulation model at the Center for Ocean–Land–Atmosphere studies suggest that Amazonian deforestation would be associated with increased precipitation in the basin of the Paraná and Paraguay Rivers and decreased precipitation in the basins of the Uruguay and Negro Rivers.

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