Streamflow in Southeastern South America and the Southern Oscillation

CARLOS R. MECHOSO

Department of Atmospheric Sciences, University of California at Los Angeles, Los Angeles, California

GONZALO PEREZ IRIBARREN

Centro de Matemática, Universidad de la República, Montevideo, Uruguay

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ABSTRACT

The relationship between the Southern Oscillation (SO) and streamflow in two major rivers of southeastern South America (Negro and Uruguay rivers) is explored for the period 1909–1989. It is found that streamflow in both rivers has a clear tendency to be below average in the period from June through December in high SO index years (cold events in the equatorial Pacific Ocean) and a slight tendency to be above average in the period from November through the next February in ENSO years. These findings are in broad agreement with previously proposed associations between extremes in the Southern Oscillation and rainfall variability in southeastern South America.

1. Introduction

It has been recognized that warm and cold events in the equatorial Pacific have relationships with anomalies in the atmospheric circulation over extratropical South America (see Aceituno 1988, and references therein). Correlations have also been recognized between the Southern Oscillation (SO) and the streamflow of rivers flowing in the tropics and extratropics of South America. Among the latter, the Paraná River (see Fig. 1) shows a negative correlation between its streamflow and the SO index (Molion and de Moraes 1987). Aceituno (1988) suggests that aspects in the variability of streamflow in the Paraná River reflect those in convective activity along a band stretching from the Amazon basin into the South Atlantic.

In two complementary papers, Ropelewski and Halpert (1987, 1989) report the results of a search for connections between the SO and rainfall anomalies around the globe. In the 1987 paper, they concentrate on ENSO years (as defined by Rasmusson and Carpenter 1983); in the 1989 paper, they concentrate on high SO index years (defined as those years during which the Tahiti–Darwin SO index remains in the upper 25%). The papers identify a relatively small number of geographical regions around the globe with spatially coherent increase or decrease in rainfall during specific subperiods of years during extreme phases of the SO.

In this paper we focus on a region where Ropelewski and Halpert (1987, 1989) and Aceituno (1988) find significant relationships between extremes in the SO and rainfall anomalies. The region in question is southeastern South America, which includes southern Brazil, Uruguay, and parts of northeastern Argentina. Here, Ropelewski and Halpert (1987, 1989) find that rainfall from June through December tends to be lower than normal in years with high SO index. Also, rainfall from November through the next February tends to be higher than normal in ENSO years. (Note that the relationships between high and low SO index and anomalous rainfall hold for different periods in the seasonal cycle.) Aceituno's (1988) bimonthly correlation analysis between rainfall and the SO index is consistent with these findings.

For southeastern South America the relationships mentioned above are obtained using data from very few stations (C. Ropelewski, personal communication). In this paper we attempt to validate those relationships by using a different dataset: an 81-year record of streamflow in two major rivers in the region, the Negro and the Uruguay (see Fig. 1). We recognize that the correspondence between rainfall and streamflow is indirect and presumably strongly nonlinear. Nevertheless, it is reasonable to expect outstanding anomalies in rainfall to be associated with anomalies of the same sign in streamflow. In this sense, we consider streamflow as a proxy for rainfall.

We start in section 2 by describing the data used in this study, and by describing the characteristics of streamflow in the Negro and Uruguay rivers. Principal results are presented in sections 3 and 4. The former section studies the time series of streamflow anomalies from June through December, and the latter section

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Corresponding author address: Dr. Carlos R. Mechoso, University of California, Department of Atmospheric Sciences, 405 Hilgard Ave., Los Angeles, CA 90024.

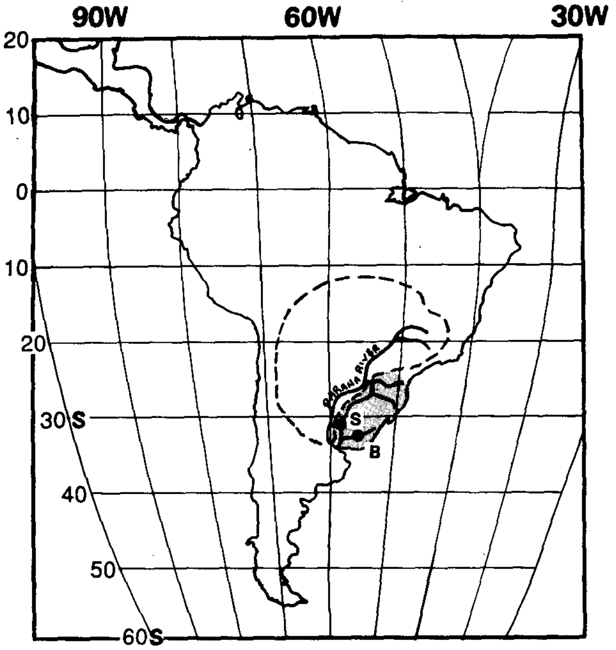

FIG. 1. Geographical location of major rivers in southeastern South America. The drainage basins of the Uruguay River are schematically indicated by the shading. The dashed line bounds the drainage basin of the Paraná River. The letters B and S correspond to Rincón del Bonete and Salto Grande, respectively.

studies the time series of streamflow anomalies from November through the next February.

2. Data and interannual variability

The dataset consists of time series for the period 1909–1989 of monthly mean streamflow at the current locations of two hydroelectric plants: Rincón del Bonete (B) on the Negro River at 33°S, 56°W, and Salto Grande (S) on the Uruguay River at 31°S, 58°W (see Fig. 1). Usinas y Transmisions Eléctricas (UTE, Uruguay's public utility company) compiled the dataset. In the process, special methods were used to guarantee consistency between values corresponding to periods before and after the hydroelectric plants were built.

The Uruguay River flows mostly in the north–south direction, between about 25° and 35°S, and the Negro River flows mostly in the east–west direction around 33°S. No significant contribution to these time lags from snow melting is expected. The time lags between peak precipitation and peak streamflow in either river are expected to be much shorter than the periods considered in this study, which are either 7 months (June to December) or 4 months (November to February).

The annual cycle of streamflow at B and S is shown in Fig. 2. The monthly mean streamflow at both B and S is at a minimum in January, increases until July, and decreases in August. Later in the year, the streamflow at B continues to decrease, while that at S increases again to an absolute maximum in October. This different behavior reflects the higher complexity of the extended drainage basin of the longer Uruguay River.

We now inspect the monthly streamflow anomalies at B and S ("anomaly" refers to the deviation with respect to the mean over the period 1909–1988). A convenient way to display these anomalies is to plot $A(t)$, obtained by interpolation of the discrete function A_n defined by the recurrence relation

$$A_0 = 0, \quad A_{n+1} = A_n + Q_n, \qquad (1)$$

where n is the number of months since January 1909; Q_n is the streamflow anomaly for month n; $A = 0$ for the last month in the dataset; $A(t)$ increases or decreases in time if the streamflow is above or below its mean value. Figure 3 shows $A(t)$ for B and S. In both locations, $A(t)$ strongly decreases during the major droughts that developed in southeastern South America around

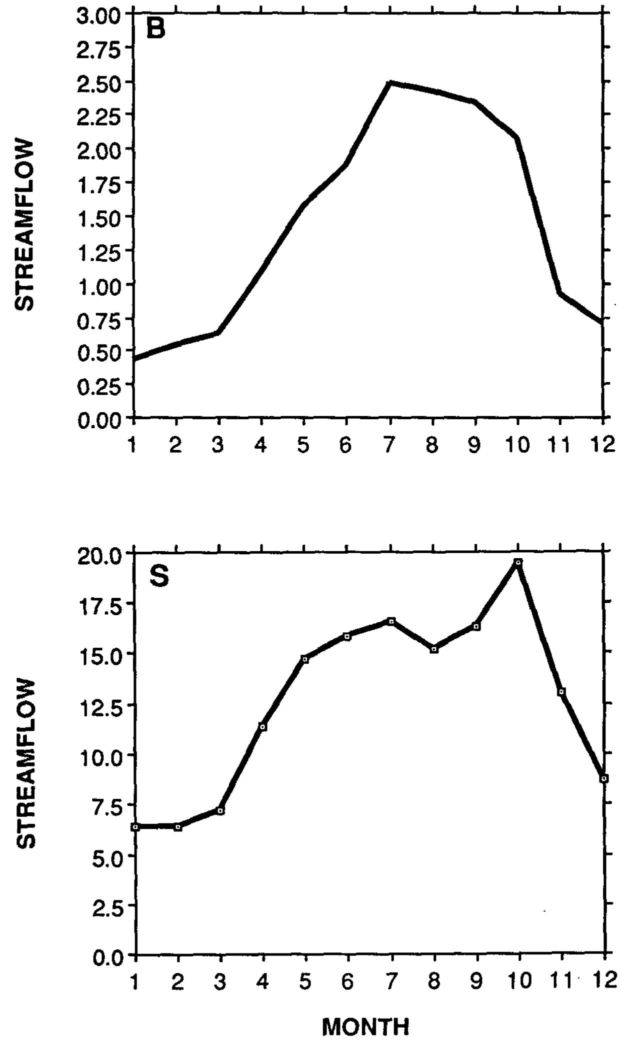

FIG. 2. Seasonal evolutions of the monthly mean streamflow (km^3 per month) at B and S.

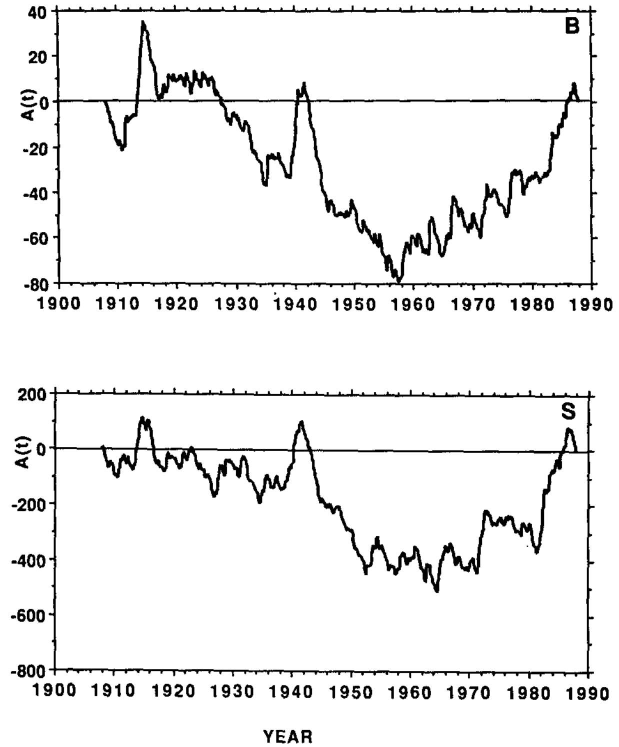

FIG. 3. $A(t)$ (km^3) defined in Eq. (1) of the text for B and S.

1917 and 1943. Only the first of these two major droughts coincide with an extreme phase of the SO.

3. Streamflow from June through December in high SO index years

High SO index years in our dataset and that of Ropelewski and Halpert (1989) are 1909, 1910, 1916, 1917, 1924, 1928, 1938, 1950, 1955, 1956, 1964, 1970, 1971, 1973, and 1975. Our study includes the 1988 event. We are interested in the period from June through December.

a. Rincón del Bonete (B)

Figure 4 show the time series of streamflow anomalies at B from June through December. There is substantial interannual variability. Negative values with large magnitude persist for more than one year in the periods of strong droughts around 1917 and 1943.

The solid circles in Fig. 4 identify high SO index years. We notice that 12 of the corresponding streamflow anomalies are negative and 4 are positive. If the probability of each sign is taken as 0.5, then that of 12 (or more than 12) negative and 4 (or less than 4) positive signs comes to 3.8×10^{-2}, which is significantly low. It appears, therefore, that the streamflow at B (Negro River) from June through December in high SO index years is significantly more likely to be below than above average.

The distribution of streamflow anomalies at B from June through December is not known a priori. Thus, we apply techniques of nonparametric inference in our analysis. The approximate equal number of positive and negative values in our sample (41 and 40, respectively) suggests a distribution symmetric about the origin. To test for symmetry, we apply Wilcoxon signed-ranks test (see Gibbons 1985). For our time series, the sum of the ranks of the negative anomalies is $T^- = 1780$. We can then compute

$$Z = [4T^- - n(n + 1)]/[2n(n + 1)(2n + 1)/3]^{1/2}, \qquad (2)$$

where $n = 81$, to obtain $Z = 0.5626$. By using the normal distribution we find (see Gibbons 1985) that the probability of obtaining such a Z (or larger) is about 0.287. It follows that there are no indications of lack of symmetry in the distribution of streamflow anomalies at B from June through December. On the other hand, the same procedure applied to the subset corresponding to high SO index years results in a Z for which the normal distribution gives a probability of less than 2×10^{-2}, a significant low value. We conclude that there is a strong indication that the distribution of streamflow anomalies at B from June through December in high SO index years is asymmetric about the origin—more precisely, that negative values are more probable than positive values.

We can also proceed without considerations on the symmetry of the distribution of streamflow anomalies. The method is based on the Mann–Whitney test for two samples (see Gibbons 1985). In this case, we test the hypothesis that the two medians are equal against the alternative that the median of the distribution of streamflow anomalies is larger than that of the subset corresponding to high SO index years. The test gives a probability of 8.4×10^{-4} (or less) that the former hypothesis is valid. This is a very significant low value, which is consistent with a clear tendency that the

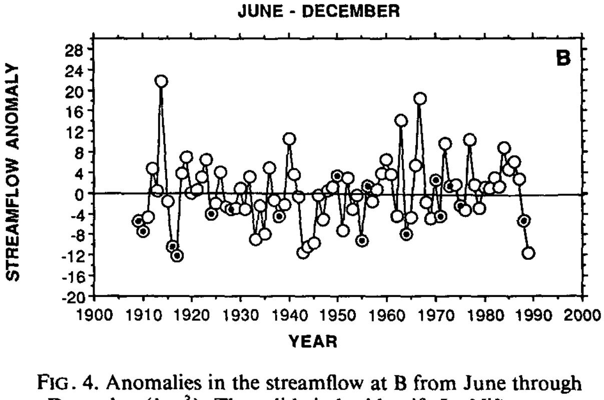

FIG. 4. Anomalies in the streamflow at B from June through December (km^3). The solid circles identify La Niña years.

streamflow at B from June through December during the high index phase of the SO is below the mean streamflow for the period.

b. Salto Grande (S)

Figure 5 shows the time series of anomalies in the streamflow at S from June through December. As in Fig. 4, there is substantial interannual variability, with strong negative values persisting for more than one year in the periods of strong droughts around 1917 and 1943. Again, years with high SO index show 12 negative values and only 4 positive values. Among the latter, only 1973 has the same property in the record for B.

There are also indications of lack of symmetry in the distribution for the values corresponding to high SO index years (identified by the solid circles in Fig. 3). Therefore, we use once more the Mann–Whitney test for two samples. The test gives a probability of 10^{-2} (or less) that the distribution of streamflow anomalies at S from June through December and that of the subset corresponding to high SO index years have the same median. Since this is a significant low value, we conclude that our findings for B also hold for S.

4. Streamflow from November through next February in ENSO years

ENSO years in our dataset and that of Ropelewski and Halpert (1987) are 1911, 1914, 1918, 1923, 1925, 1930, 1932, 1939, 1941, 1951, 1953, 1957, 1965, 1969, 1972, 1976, 1982, and 1986. We are interested in the period from November through the next February.

a. Rincón del Bonete (B)

The corresponding time series are shown in Fig. 6. The solid circles in Fig. 6 identify ENSO years. In this case, 10 of the corresponding streamflow anomalies are positive and 8 are negative. Notice, however, that positive values tend to have large magnitude, while negative values tend to have small amplitude. Consequently, we test the hypothesis that the distributions of streamflow anomalies from November through the next February and that of the subset corresponding to ENSO years have the same median against the alternative that the median of the former distribution is smaller than that of the latter distribution. The Mann–Whitney test gives a probability of 10^{-2} (or less) that the two medians are the same. This is a very significant low value.

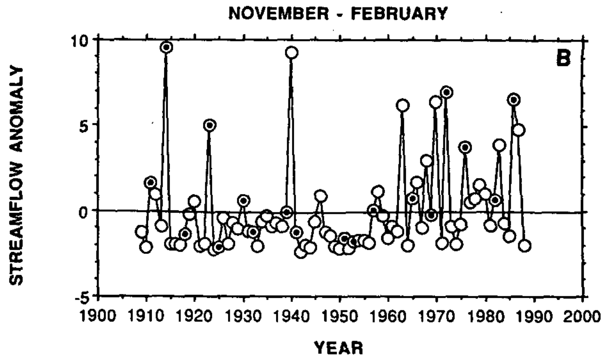

FIG. 6. Anomalies in the streamflow at B from November through the next February (km^3). The solid circles identify El Niño years.

Our results suggest, therefore, that the streamflow at B from November through the next February in ENSO years has a slight tendency to be above average, with values that are occasionally well above average.

b. Salto Grande (S)

The corresponding time series are shown in Fig. 7. In this case, there are 11 positive values and 7 negative values, with the former showing a tendency to have larger magnitude that the latter. The Mann–Whitney test gives a probability of 1.33×10^{-3} (or less) that the distributions of streamflow anomalies from November through the next February and that of the subset corresponding to ENSO years have the same median. This is a very significant low value. We conclude that our findings for B also hold for S.

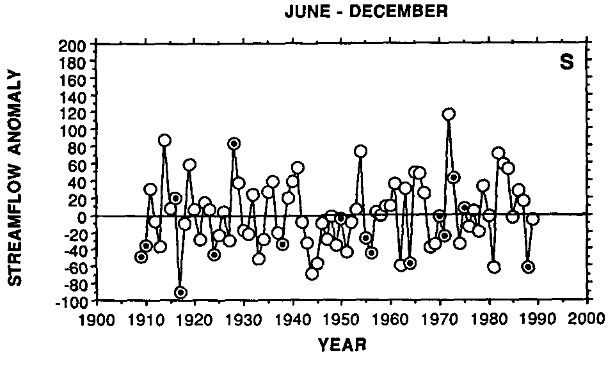

FIG. 5. As in Fig. 2 except for S.

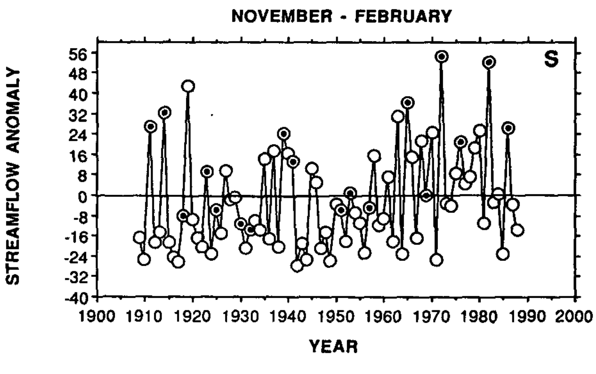

FIG. 7. As in Fig. 4 except for S.

5. Summary

We have examined the record of monthly mean streamflow in two major rivers of southeastern South America, the Negro and the Uruguay, during the period 1909–1989. Currently, there are four major hydroelectric plants (three national and one international) along these large rivers.

We inspected the existence of relationships between anomalous streamflow and the SO. Ropelewski and Halpert (1987, 1980) found that rainfall from June through December is lower than normal during the high index phase of the SO. They also found that rainfall from November through the next February is higher than normal during ENSO years. Motivated by these findings, we considered separately the streamflow for the periods June through December, and November through the next February.

Our analyses show a clear tendency for the streamflow in both the Negro and Uruguay rivers for the period June through December in high SO index years (cold events in the equatorial Pacific Ocean) to be below average. Our analyses also show that the streamflow in both the Negro and Uruguay rivers for the period November through the next February in ENSO years has a slight tendency to be above average, with values that are occasionally well above average.

We recognize that the relation between rainfall and streamflow in rivers is not a simple one. One would expect, however, low or high streamflow in years of low or high rainfall in the corresponding river basin. Our findings, therefore, provide an indirect confirmation of those of Ropelewski and Halpert (1987, 1989) and Aceituno (1988) concerning the association between cold and warm events in the equatorial Pacific and drought/flood over southeastern South America. Such a confirmation is important because the original conclusions were supported by very few data. Relationships of the type reported here are of high interest for the effective management of crucial water resources.

Two other points are raised by this study. First, only one of the major droughts in the record is simultaneous with a cold event in the equatorial Pacific. This shows that, as expected, these events are not the only predictor for drought in the region. Second, while there are qualitative similarities in the results obtained for the streamflow anomalies in the Negro and Uruguay rivers, there are also quantitative differences in the estimates of statistical significance. These differences suggest that the corresponding river basins do not entirely belong to the same rainfall regime.

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