Solar Forcing of the Stream Flow of a Continental Scale South American River

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Solar forcing on climate has been reported in several studies although the evidence so far remains inconclusive. Here, we analyze the stream flow of one of the largest rivers in the world, the Paraná in southeastern South America. For the last century, we find a strong correlation with the sunspot number, in multidecadal time scales, and with larger solar activity corresponding to larger stream flow. The correlation coefficient is $r = 0.78$, significant to a 99% level. In shorter time scales we find a strong correlation with El Niño. These results are a step toward flood prediction, which might have great social and economic impacts.

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Introduction.—Evidence of a solar influence on climate has been traditionally found on records of Northern Hemisphere temperature [1], or sea surface temperature [2], usually related to changes in solar irradiance [3,4]. Also, a link between solar activity and cloud cover through the action of cosmic rays has been proposed [5] and widely discussed [6]. Recently, a number of studies took a new approach to the problem, looking into paleoclimatic records of atmospheric moisture. For example, evidence was found of solar influence on the Asian monsoon [7–11], in the drought conditions in Africa [12] and Mexico [13], and in general in tropical precipitation regimes [14]. The influence of solar activity on regional precipitations was also found in experiments with a global climate model [15].

Here, we take a different approach to the problem, looking into a different climatic variable, also related to moisture, in a different time scale: we study the stream flow of the Paraná River during the last 100 years [16].

River stream flows are excellent climatic indicators since they integrate precipitations, infiltrations, and evapotranspiration over large areas. In particular, those rivers with continental scale basins smooth out local variations, and can be particularly useful to study global forcing mechanisms. Moreover, knowledge and/or prediction of stream flow regimes is fundamental for different social and economic reasons, from the prediction of floods and droughts to planning of agricultural or hydroenergetic conditions.

Data.—The Paraná is one of the largest rivers in the world: with a basin area of over 3 100 000 km^2 and a mean stream flow, during the last two decades of the 20th century, of 20 600 m^3/s, the Paraná is the fifth river of the world according to drainage area and the fourth according to stream flow. With its origin in the southernmost part of

the Amazon forest, it flows south collecting water from the countries of Brazil, Paraguay, Bolivia, Uruguay, and Argentina, and forms one of the mightiest deltas of the world before its outlet in the Plata River, a few kilometers north of the city of Buenos Aires. Because of the fact that, unlike other rivers of similar size like the Amazon or the Congo, it flows through heavily populated areas, and that it is navigated by overseas trade ships, it has one of the longest stream flow data series, which covers the last century.

Here we analyze the stream flow data measured at a gauging station located in the city of Corrientes, 900 km north of the outlet of the Paraná. It is measured continuously from 1904, on a daily basis. The Paraná's hydrological year goes from September to August, with maximum stream flow in the (Southern Hemisphere's) summer months of January, February, and March. We therefore build our yearly series integrating the flow from September to August of the next year. The data are shown in Fig. 1(a), together with the trend obtained with a low-pass Fourier filter with a 50 years cutoff.

It can be seen that the flow of the Paraná is larger in the last three decades, with a mean value almost 20% larger than that of the first 70 years of the 20th century. In particular, the stream flow during the last 30 years has increased in the months in which the flow is minimum, May to December, while the flow remains more or less constant during the months of maximum. This trend has already been noticed, and was attributed to Amazonian deforestation [17], which should facilitate water drainage. However, the same trend is also found in other rivers of the region like the Iguazú, whose sub-basin has not undergone significant changes in land use during the 20th century [18]. On the other hand, this trend can be considered to
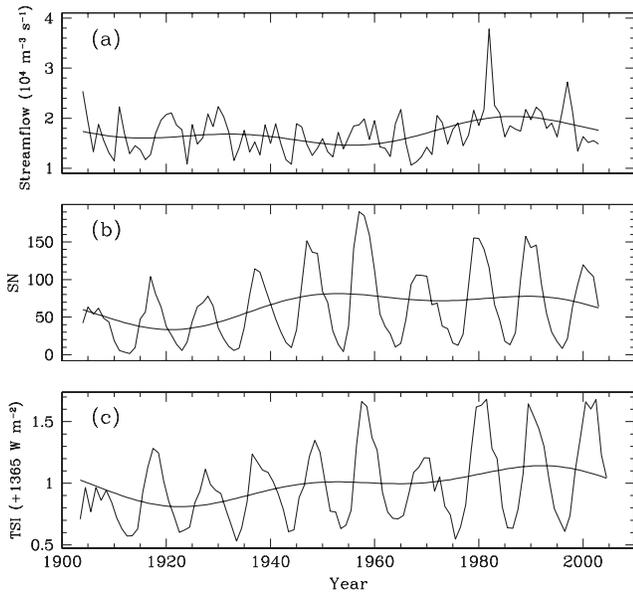
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FIG. 1. (a) Paraná's annual stream flow at the Corrientes gauging station. (b) Yearly international sunspot number (S_N). (c) Solar irradiance reconstruction [22]. The secular trends, obtained with a low-pass Fourier filter with a 50-yr cutoff, are shown as thick lines.
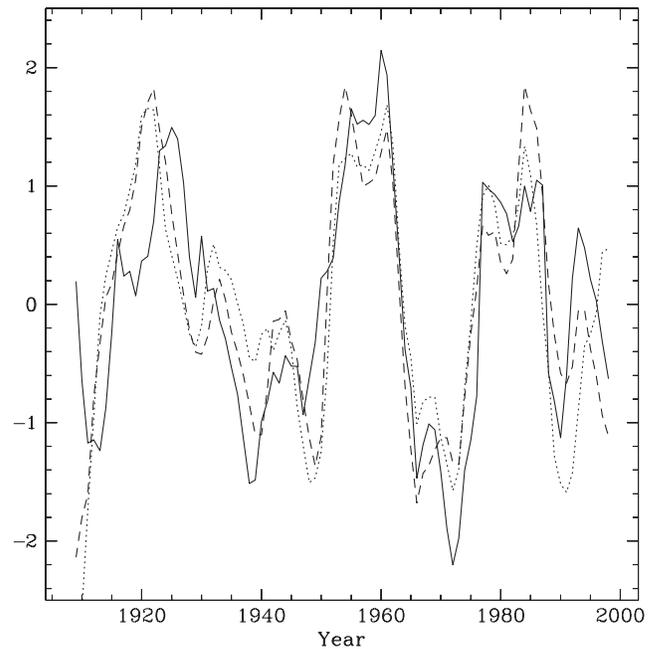

FIG. 2. The detrended time series for the Paraná's stream flow (full line), the sunspot number (dashed line), and the irradiance reconstruction (dotted line). The detrended series were obtained by subtracting from each data series the corresponding trend, shown as a thick line in Fig. 1, and were smoothed by an 11-yr running mean to smooth out the solar cycle. The series were normalized by subtracting the mean and dividing by the standard deviation, to avoid introducing arbitrary free parameters. The Pearson's correlation coefficient of the stream flow data with the sunspot number is $r = 0.78$, and with the irradiance reconstruction is $r = 0.69$.

be an integral part of the large-scale variations of the climate system [19]. It should be noted that southeastern South America is one of the principal regions of the globe where land surface temperature has been increasing since 1900 [20].

As a solar-activity indicator we consider the yearly sunspot number (S_N) [21], which is shown in Fig. 1(b) together with its trend, obtained in the same way as that for the stream flow. Alternatively, the irradiance reconstruction by Wang *et al.* [22] can be used as a solar-activity indicator. It differs somehow from the sunspot record since irradiance depends more on bright regions on the solar surface.

In Fig. 2 we show the detrended time series for stream flow, S_N and the irradiance reconstruction. In all cases we have substracted the trend shown in Fig. 1 from the annual data, and we have performed an 11 yr running-mean to smooth out the solar cycle. When plotting together different quantities, two free parameters are usually introduced, namely, the offset and the relative scales. To avoid these two artificial parameters, we have normalized the three quantities by substracting the mean and dividing by the standard deviation of each series.

Results.—Visual agreement between the Paraná's stream flow, the sunspot number, and the irradiance reconstruction shown in Fig. 2 is quite remarkable. The Pearson's correlation coefficient between stream flow and S_N is $r = 0.78$, and between stream flow and irradiance is $r = 0.69$. We performed a t-student test to check the significance of these correlations, reducing the number of effective points to

take into account the autocorrelation of the series and the smoothing, and we obtained a significance level higher than 99.99% in both cases. We also analyzed the significance level of the correlations with a nonparametric random-phase test [23]. For the S_N series, we obtained that only a 0.4% of the random series presented a correlation coefficient greater than 0.78. In this way, we obtain a significance level of 99.6% for the correlation between stream flow and S_N. For the irradiance reconstruction, the significance obtained with this method is larger than 99.99%.

Recently, a mechanism has been proposed for the influence of solar activity on climate, involving the modulation of galactic cosmic rays (GCR) by the interplanetary magnetic field associated with the solar wind and, therefore, with solar activity. In this picture, GCR would affect cloud formation on Earth, through ionization of the terrestrial atmosphere. Therefore, periods of higher solar activity, when the interplanetary magnetic field is larger, and therefore less GCR hit Earth, the cloud cover would be smaller. For this reason, it is particularly interesting to check whether there is a particularly strong correlation between the Paraná's discharge and GCR.

Therefore, we have also checked the correlation with two other solar-activity indexes. First, we considered the neutron count at Climax, Colorado, available since 1953 [24]. Since neutrons are produced when GCR hit the upper atmosphere, neutron count is a direct measure of GCR flux. Furthermore, since GCR flux in different parts of the world depend only on latitude, following the strength of the terrestrial magnetic field, Climax's values are representative of GCR flux everywhere.

The other index we used was the aa index, which is a measure of the disturbance level of the Earth's magnetic field based on magnetometer observations of two, nearly antipodal, stations in Australia and England [25], and it is available since 1868 [26]. It is worth pointing out that the aa index follows the envelope of solar activity, and while S_N returns to zero at each solar minimum, aa minima reflect the long-term level of solar activity seen in Fig. 1(b). Since the Earth's magnetic field, which is affected by the solar wind, determines how much of the GCR flux ultimately reaches the Earth, aa can also be used to test the GCR-climate hypothesis.

In both cases, we found a correlation with Paraná's stream flow, as expected since all indexes of solar activity are correlated between each other. However, the correlations shown in Fig. 2 are the largest, pointing to a more direct correlation with solar irradiance than with GCR.

An important point to be stressed regards the sign of the relationship between solar activity and river discharge reported here, which implies that wetter conditions in this area coincide with periods of higher solar activity. This is in agreement with paleoclimatic studies of the Asian monsoon [8,9,27] which report an increase in monsoon during periods of increased solar activity. Also, increases in solar activity were found to be correlated with increased moisture over Alaska during the Holocene [28], and similar results were found in simulations of climate during a period of reduced solar activity known as the Maunder minimum [29].

In contrast, studies in East Africa report severe droughts during phases of high solar activity and increased precipitation during periods of low solar irradiation [12]. To explain these differences it has been proposed that increased solar irradiation causes more evaporation in equatorial regions, enhancing the net transport of moisture flux to the Indian subcontinent via monsoon winds [8]. A similar mechanism was found in simulations with a climate model, in which enhanced solar forcing produces greater evaporation in relative cloud-free regions in the subtropics, and the resulting moisture then converges into the precipitation convergence zones [15].

In the American continent, droughts in the Yucatan Peninsula have been associated with periods of high solar activity and even proposed to explain the Mayan decline [13], in contrast with the results found here. This is in agreement with an inverse correlation that was found between the southern and northern regions of South America, with dry periods in the south corresponding almost in phase to humid intervals in the north and vice versa [30].

The fact that solar influence is different in different parts of the world is of particular importance when assessing the proposed relationship between solar activity and climatic change, since it points out to modifications in circulation patterns or other mechanisms that do not globally affect climatic variables like moisture, but affect their distribution instead.

Finally, in Fig. 3 we show the high frequency variations of the Paraná's stream flow, obtained by subtracting the 11-year-running-mean from the yearly data. Also shown is the Niño1+2 index, averaged from September to August next year, to coincide with the hydrological year of the river. El Niño1+2, which is available since 1950, is a measure of the sea surface temperatures in the Equatorial Pacific Ocean, close to the South American coast $(0°–10°$ S, $80°–90°$ W) [31]. In this case, a very good accordance between both curves can be seen, with a correlation coefficient $r = 0.65$ and a significance larger than 99.99%. In particular, the large annual discharges of 1982 and 1997 are associated with two exceptional El Niño episodes.

This relation between the Paraná's stream flow and the ENSO phenomenon and, in particular, the sea surface temperatures in a region of the tropical Pacific, was already
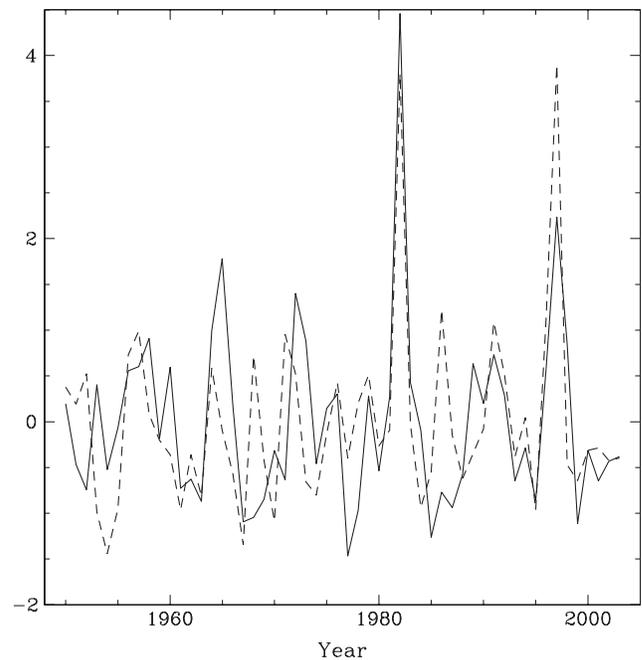

FIG. 3. Paraná's stream flow minus the multidecadal component (full line) compared with the Niño1+2 index (dotted line), which is available from 1950. Both series were normalized by subtracting the mean and dividing by the standard deviation, to avoid introducing arbitrary free parameters. The Pearson's correlation coefficient for the whole series is $r = 0.65$.

used in flood predictions in this basin [32]. A similar correlation was also found for the Indian monsoon [33].

Conclusions.—Stream flow variability of the Paraná river has three temporal components: on the secular scale, it is probably part of the global climatic change, which at least in this region of the world is related with more humid conditions; on the multidecadal time scale, we found a strong correlation with solar activity, as expressed by the sunspot number, and therefore probably with solar irradiance, with higher activity coincident with larger discharges; on the yearly time scale, the dominant correlation is with El Niño.

These correlations can be used for flood prediction: a regression between Paraná's stream flow (S), the sunspot number filtered as in Fig. 2 (S_{Nf}), and El Niño1+2 (N_{12}), gives

$$S = (63.6 \pm 59.3)S_{Nf} + (3.6 \pm 0.6)$$
$$\times \, 10^2 N_{12} + (6.5 \pm 1.3) \times 10^4$$

between 1949 and 1999, with a Pearson correlation coefficient $r = 0.66$, significant to 99.99%.

Early flood prediction, in fact, has large social and economic impacts: During the last flood, in 1997, $180\,000$ km^2 of land were covered with water, $125\,000$ people had to be evacuated, and 25 people died. In all, the three largest floods of the Paraná during the 20th century caused economic losses of five billion dollars.

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