The Paraná River Response to El Niño 1982–83 and 1997–98 Events

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(Manuscript received 23 June 1999, in final form 20 March 2000)

ABSTRACT

The most severe flooding of the twentieth century in the Argentine section of the Paraná River occurred during the strong El Niño (EN) event of 1983. During the 1997–98 EN episode, discharge anomalies in the Paraná basin, although of the same sign as those of the 1982–83 event, were much smaller. The main differences were observed during January–March and June–July of the year following the starting date of the event, when the 1982–83 discharge anomalies were considerably larger. This study explores this issue as well as the relationship between convection anomalies in the Paraná basin and tropical Pacific and South Atlantic sea surface temperature (SST) anomalies.

The correlation between convection in the upper and middle Paraná and Iguazú basins, as measured by outgoing longwave radiation, and SST in both the Niño-1+2 and Niño-3 regions is statistically significant for most of the period November–July, reaching the maximum value in the three basins during May. However, the analysis of the higher Paraná streamflows during EN events since 1904 indicates that they were decisively influenced by the Niño-3 SST anomalies. Therefore, the exceptional discharge of the Paraná River of 1983 is attributed principally to the exceptionally warm SST temperatures in the Niño-3 region during April–June 1983.

During January 1983, there was a pattern of SST anomalies in the South Atlantic with warm water to the north of the South Atlantic convergence zone, especially west of 20°W, and cold water to the south. This pattern is correlated with convection over the upper and middle Paraná basins, as occurred in 1983. During January 1998, the SST pattern was substantially different from what should be expected to be associated with positive anomalies in the convection field over the middle Paraná basin. This feature could be responsible for the small convection over this basin during January 1998.

1. Introduction

Starting in May 1983, the most severe floods of the twentieth century occurred in the Argentine section of the Paraná River, the most important of the Río de la Plata tributaries. Although a documented study is not available, this flood has been generally attributed to the exceptionally strong El Niño (EN) event that took place during late 1982 and the ensuing months of 1983. This belief was based on the fact that the Paraná River basin is part of a region that has a strong precipitation signal during ENSO (EN–Southern Oscillation) events, as reported by Ropelewski and Halpert (1987, 1996), Kiladis and Diaz (1989), and Grimm et al. (2000). Moreover, Aceituno (1988) showed that the Southern Oscillation index and the discharge of the Paraná River at Corrientes were negatively—although weakly—correlated during the November–April period.

Others studies on the relationships between ENSO events and streamflow variability in some rivers of the region indicate that positive discharge anomalies are associated with the warm phase of ENSO events. Mechoso and Pérez (1992) showed that there is a tendency for the discharge in the Negro and the Uruguay Rivers to be above the median during the period November–February of EN years.

On the other hand, the influence of sea surface temperature (SST) anomalies of the Atlantic Ocean on precipitation in the Paraná basin cannot be disregarded without examination. Although this issue has not yet been fully examined, the results of Díaz et al. (1998) suggest that there could be some relation. They investigated the annual cycle of precipitation in the nearby region of Uruguay and southern Brazil and found links between its anomalies and those in the southwestern

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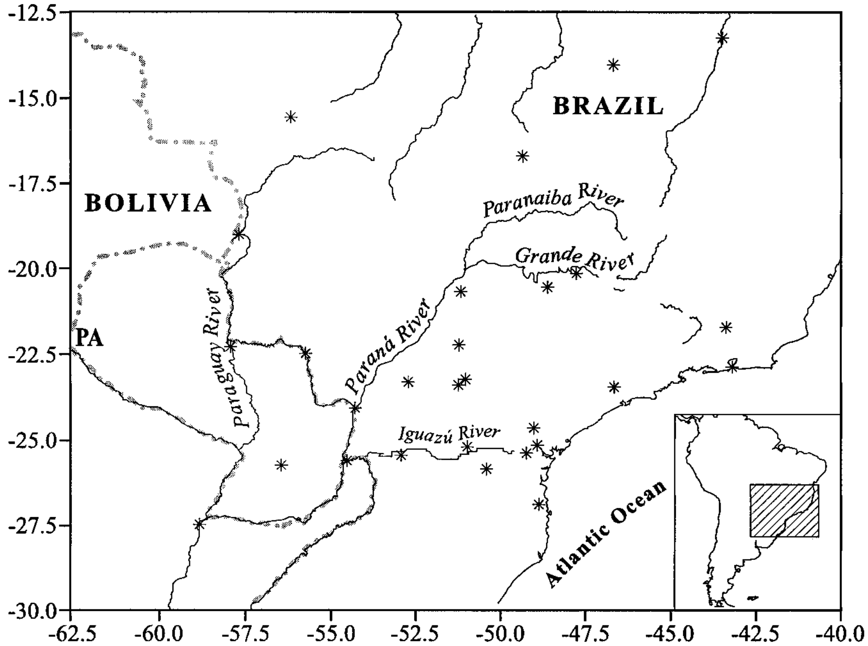

FIG. 1. Paraná river basin and main tributaries. (*) Precipitation stations used in this study.

Atlantic Ocean SST during the months of October–December and April–July.

The 1983 Paraná flood produced a huge economic loss and social as well as environmental impacts. Hence, it is important to understand its relationship with the 1982–83 EN not only from the scientific point of view but also to help to prevent future disasters. Therefore, the objective of this paper is to document the discharge anomalies of the exceptional 1982–83 flooding event and to study their relation with the also exceptional EN 1982–83 episode. In particular, it is focused on exploring what features of this episode were determinant in the 1983 Paraná flood.

Data are discussed in section 2, and in section 3 the annual streamflow cycles of the Paraná and its tributaries are described, providing a necessary background for the discussion of the discharge anomalies during the 1982–83 flooding event in the Paraná basin in section 4. In section 5, the interannual statistical relationship of the convective activity over the Paraná basin with EN SST is explored. Streamflows during EN events of the period 1904–76, when the river was essentially unregulated, are analyzed in connection with EN SST in section 6. During 1997–98 there was another intense EN event, but the streamflow anomalies in the Paraná, although important, were much smaller than those observed during the 1982–83 event. To understand further the 1983 exceptional flood, the 1998 case is discussed in section 7. Both events are compared using outgoing longwave radiation (OLR) anomalies, which serves as proxy data for precipitation in tropical latitudes, avoiding the comparison between regulated discharges. In section 8, the influence of the South Atlantic SST on convection anomalies in the Paraná basin is analyzed, and section 9 summarizes results and conclusions.

2. Data

The Paraná River begins at the confluence of the Grande and Paranáiba Rivers, and ends at the Río de la Plata, near the Atlantic Ocean (Fig. 1). It runs in a north–south direction through most of the basin, turning westward from Posadas to Corrientes (Fig. 2). The main tributaries of the Paraná are the Paranápanema River in the north and the Iguazú and the Paraguay Rivers, upstream from the gauging stations at Posadas and Corrientes, respectively. Upstream from Jupiá, the river is known as upper Paraná and between this location and Corrientes as middle Paraná. We identify here the upper Paraguay basin upstream from Corumbá, and the lower Paraguay basin from Corumbá to the confluence with the Paraná. The former includes a very flat area with large wetlands and marshes, known as the Pantanal (Fig. 2). This geomorphology influences the hydrological behavior, causing a half-year lag between rainfall and the streamflow in the lower Paraguay (Almeida and Barros 1999). García and Vargas (1996) studied the discharge series in the Río de la Plata basin and assessed the information available from gauging stations. In this study, we have analyzed discharges at Jupiá, Guairá, Posadas, and Corrientes on the Paraná River; Capanema on the Iguazú River; and Puerto Bermejo on the Paraguay River, which were selected according to the results presented by García and Vargas (1996). Because the most important tributaries of the Paraná in terms of their flows are upstream from Corrientes, there are no

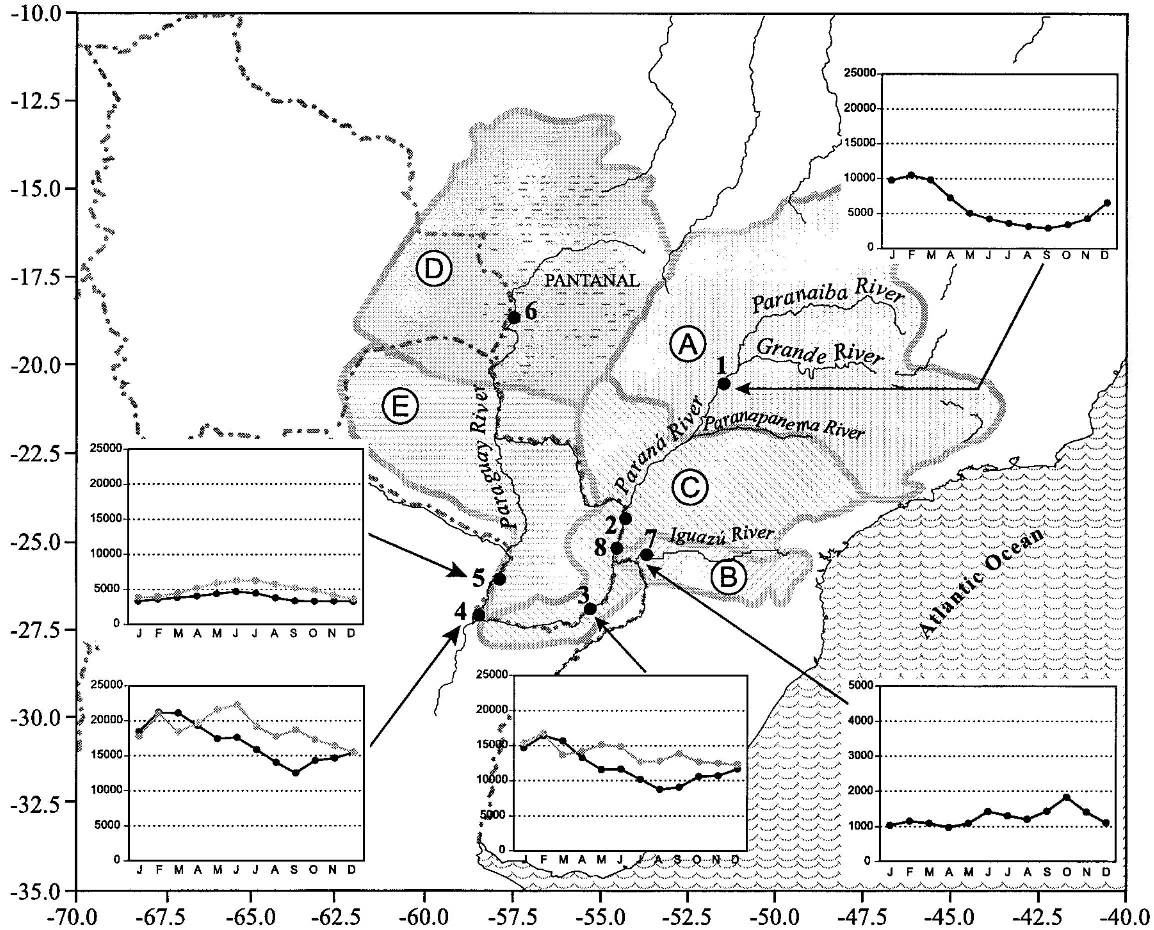

FIG. 2. Gauging stations in the Paraná, Paraguay, and Iguazú Rivers (1: Jupiá, 2: Guairá 3: Posadas, 4: Corrientes, 5: Puerto Bermejo, 7: Capanema). Discharge ($m^3\ s^{-1}$) annual cycle of the rivers at different gauging stations are included for 1931–80 (black dots) and 1984–91 (gray dots). Location of Corumbá (6) and Itaipú (8) and subbasins of the Paraná River are also indicated (A: upper Paraná, B: Iguazú, C: middle Paraná, D: upper Paraguay, E: lower Paraguay).

important changes in discharges downstream from that location. For this reason, the analysis of discharge series does not include any gauging stations downstream from Corrientes.

The sparse precipitation data available make any spatial average procedure an unreliable estimate of the actual rainfall poured over each basin. In addition, many of the monthly precipitation series present numerous gaps, and, in certain cases, it takes some years before the data are available. The use of OLR data in the Iguazú, Paraná, and Paraguay basins is explored to assess their adequacy as an estimate of the water drained toward the rivers at monthly scale. Although it does not properly represent the actual rainfall over a given area and period of time, it has some advantages, such as being spatially continuous and rapidly available. OLR has been frequently used as an index of deep tropical convection because it responds strongly to variations in cloudiness at low latitudes. Low values of OLR indicate major convective systems with high and cold cloud tops and are associated with rainfall and latent heat release. Many authors have studied interannual or intraseasonal tropical convection variability as revealed by OLR (e.g., Heddinghaus and Krueger 1981; Liebmann and Hartmann 1982; Kousky 1988; Trenberth and Guillemot 1996) or used OLR as a quantitative estimate of rainfall (Lau and Chan 1983; Arkin and Meisner 1987; Yoo and Carton 1988; Morrissey and Graham 1996). Morrissey and Graham (1996) considered that the level of noise in OLR is substantially reduced when applied to monthly averages, making it a useful index of precipitation.

OLR is remotely sensed from National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites that pass over each region twice a day. It has been monitored continuously since June 1974. The OLR data are spatially averaged in a $2.5° \times 2.5°$ grid covering the region between 12.5° and 27.5°S and between 42.5° and 62.5°W. The periods covered were June 1974 to December 1994, with gaps from March to December 1978 and November 1997 to July 1998. To reduce errors arising from the different equatorial crossing times, day and night radiances were averaged to daily values. OLR less than 240 W m^{-2} was considered indicative of convective activity. This value was used by Kousky (1988) to elaborate a climate description of OLR for the South American sector north of 30°S and is close to the limit of 235 W m^{-2} defined by Moron (1995) in a study of the variability of the African convection center. Therefore, for each day i and grid point j, the differences d_{ij} were calculated as

$$d_{ij} = \begin{cases} 240 \text{ W m}^{-2} - \text{OLR}_{ij} \\ \quad \text{if OLR}_{ij} < 240 \text{ W m}^{-2} \quad \text{and} \\ 0 \quad \text{if OLR}_{ij} > 240 \text{ W m}^{-2}; \end{cases} \tag{1}$$

OLR_{ij} is the daily average for the grid point j. Positive values of d_{ij} indicate convection. Monthly (N day) sums of d_{ij} were computed as

$$D_j = \sum_{i=1}^{N} d_{ij}. \tag{2}$$

For the Iguazú and the upper and middle Paraná basins, the relation between the river discharge and this OLR index, averaged over the basin, was compared with the response to the spatial average of monthly precipitation at the stations shown in Fig. 1. In this figure, it can be noted that the gauging stations are located at the basins' outlets, facilitating the comparison between discharge and basin averages of OLR and rainfall. Precipitation data from the 28 stations were obtained from the World Monthly Surface Climatology compiled at the National Center for Atmospheric Research.

Table 1 shows the cross-correlation coefficients between the monthly river discharge and the basin rainfall average as measured at these few stations on the one hand, and the OLR index on the other. In the upper and middle Paraná basins, the OLR index is better correlated with the river discharge than with the calculated average rainfall. This result is specifically valid from zero to two-month lags, in which seems to be the highest response of the river discharge to both variables. In the Iguazú case, the higher spatial density of rainfall data makes its average more representative, giving a better response than the OLR index at lag zero. The relatively small size of the basin makes the OLR data averaged in a 2.5° × 2.5° grid less representative, but, even with this disadvantage, the OLR index is well correlated with the river discharge. For the Paraguay River, as discussed later, there is a delay of approximately six months between rainfall in the upper basin and discharge at Puerto Bermejo. Besides, there are no discharge measurements on the river near the border of the upper and lower basins, and therefore an analysis similar to the one made for the Paraná and Iguazú basins cannot be performed. Based on these results, we considered D_j anomalies to be a suitable variable to study river discharges in the region of this analysis.

TABLE 1. Cross-correlation coefficients R between river discharge anomalies at Jupiá (upper Paraná), Corrientes (minus discharge anomalies at Jupiá, Capanema, and Puerto Bermejo), and Capanema (Iguazú) and rainfall and D_j anomalies. Significant correlation coefficients for 95% confidence level are boldface. (Independent monthly discharge anomalies were estimated to be every five months on the upper Paraná, every three months on the middle Paraná, and every month on the Iguazú.)

Subbasin	Lag	R (rainfall–river discharge)	R (OLR–river discharge)
Upper Paraná	0	0.14	0.26
	1	0.28	**0.36**
	2	0.27	0.27
	3	0.18	0.12
	4	0.18	0.13
Middle Paraná	0	0.11	**0.32**
	1	**0.35**	**0.45**
	2	0.18	**0.37**
	3	0.08	0.28
	4	0.07	0.27
Iguazú	0	**0.71**	**0.52**
	1	**0.50**	**0.46**
	2	**0.29**	**0.31**
	3	**0.15**	**0.25**
	4	**0.18**	**0.20**

To study the relationships between convection anomalies and SST, both in the tropical Pacific and in the Atlantic, SST data for 1904–94 were taken from the Meteorological Office Historical Sea Surface Temperature, version 5 (Rayner et al. 1996). SST data for 1997–98 years were obtained from NOAA's Climate Prediction Center.

A considerable number of dams on the upper Paraná River have modified some features of the annual cycle of the river discharge. The greatest changes began around 1980, and the reservoir capacity increased when Itaipú, the largest dam in the world, started to operate in 1983. Consequently, it would be important to remove the effects of the dam regulation from the streamflow records. However, the unregulated records are not available. Therefore, it was impossible to recover the unregulated flows. In any case, as will be seen later, the extreme discharge anomalies of 1983 overshadow the effects of the streamflow regulation. However, the lack of unregulated discharge data poses a severe problem for the 1983 comparison with other events with smaller streamflow anomalies, particularly in the case of the 1997–98 event. Therefore, independent data, that is, the monthly convective anomalies over the Paraná basin, were used to avoid this problem whenever the EN events after 1983 were discussed. In addition, the EN events prior to 1980, when the river was practically unregulated, were analyzed in connection with the outstanding features of the 1982–83 event.

At this point, it is clear that various parameters taken from different sources and datasets were employed. This mixture of data is a consequence of the need to maximize the scarce data available and of the subject studied.

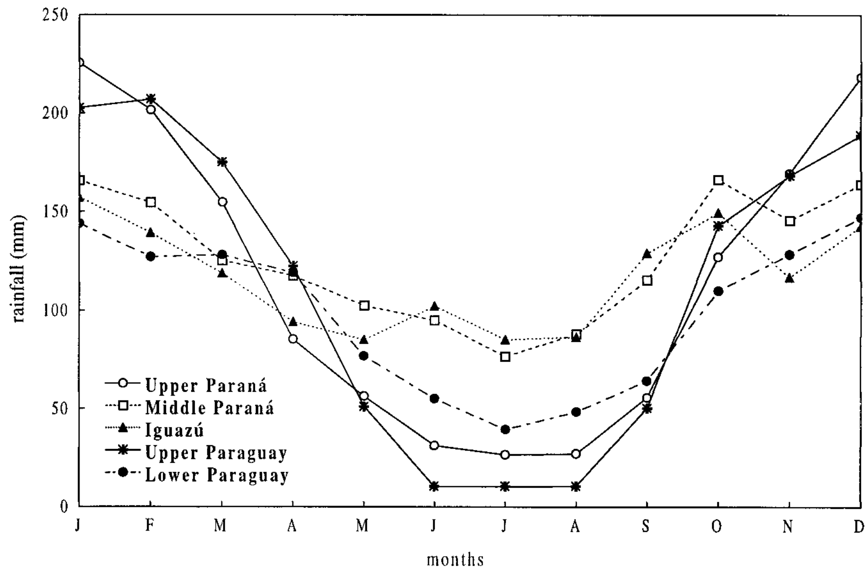

FIG. 3. Rainfall annual cycle for the basins defined in Fig. 2 (1956–91).

Besides, gauging stations—and even datasets—cover different periods of time, either because the observing systems improved over time, or because new observing technologies have evolved, as in the case of OLR. Naturally, these aspects have influenced the choice of methodology options taken at each step of the study.

3. Hydrological description

a. The annual cycle

Figure 2 shows the annual cycle of the Paraná River at three different gauging stations and at two of its tributaries, the Paraguay and Iguazú Rivers, for the 1931–80 period, when the Paraná was practically unregulated. The Paraná regime had a peak during February and March and a minimum during August and September at all gauging stations. The maximum discharges during February and March are associated with copious austral summer rainfall over the upper Paraná basin from the intense convection organized in the South Atlantic convergence zone (SACZ). During the austral summer months, the SACZ can be seen in the mean monthly cloudiness charts as a bright band, or in the mean monthly OLR fields as a band of minimum energy connected to the intense convection over the Amazon basin (Satyamurty and Rao 1988; Figueroa et al. 1995; Nogués-Paegle and Mo 1997).

The Iguazú River annual cycle has a smaller range because the regional precipitation regime varies little throughout the year. During June–August, rainfall is produced by baroclinic activity; in the austral summer it is enhanced by the proximity of the SACZ. During September–November, there is almost the same frequency of cyclogenesis as in June–August (Gan and Rao 1991) but with higher water vapor content (Rao et al. 1996). Consequently, the Iguazú River discharge has a maximum in October, which is reflected on the Paraná River as a slight secondary maximum at Posadas (Fig. 2).

Discharge at Puerto Bermejo shows a maximum during the austral winter. This is evidence of a delay of approximately six months between the river streamflow at Puerto Bermejo and the austral summer rainfall in the upper Paraguay basin, a flat area of almost 100 000 km^2 known as El Pantanal (Almeida and Barros 1999). This maximum on the Paraguay River reinforced the secondary peak on the Paraná already observed in Posadas.

Figure 2 also shows the streamflow at Posadas, Corrientes, and Puerto Bermejo after 1983, when a change in the annual cycle caused by the large dams was to be expected. In comparison with the 1930–1981 period, Posadas and Corrientes present smaller ranges in the annual discharge cycles, with a reduction of the austral summer maxima and an increase in the maxima of the early winter. On the other hand, the mean annual discharge shows an increment of 12% at Corrientes, 16% at Posadas, and 30% at Puerto Bermejo, caused by enhanced precipitation over most of the region (Castañeda and Barros 1994). The increment of the winter peak at Corrientes is due to the combined effect of the water release from the dams on the Paraná and the larger contribution from the Paraguay River.

Figure 3 presents the annual rainfall cycle for the basins shown in Fig. 2. As can be seen, the annual amplitudes in the upper Paraguay and Paraná basins are larger than in the other basins. Summer rainfall is more abundant than winter rainfall everywhere, doubled in the Iguazú and the Middle Paraná basins, and almost 8 times larger in the upper Paraguay and the upper Paraná.

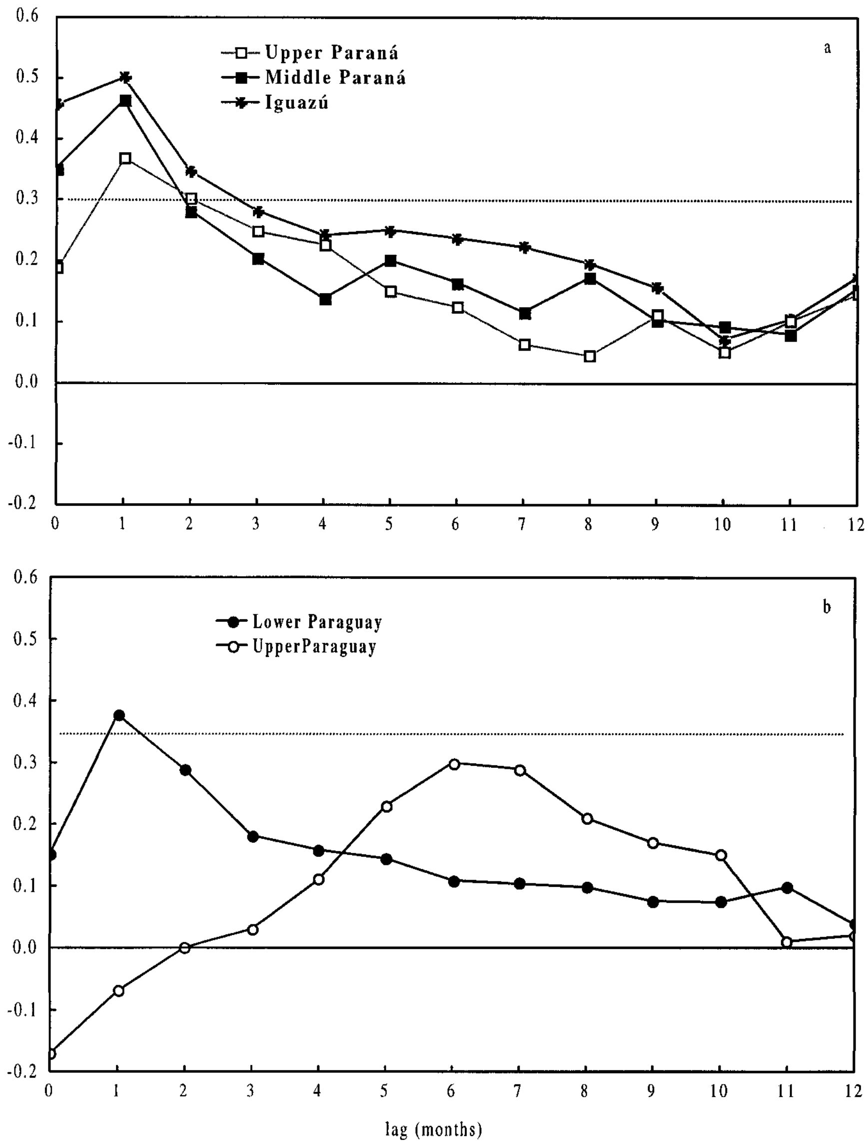

FIG. 4. Cross-correlation coefficients between discharge anomalies at (a) Posadas and (b) Puerto Bermejo and rainfall anomalies in different basins. In the case of the upper Paraguay, the OLR index was used instead of rainfall. The dotted lines indicate the 95% significance level.

This rainfall regime contributes to the attenuation of the seasonal cycle of the Paraná flows downstream. It also leads to the management of water in the dams in a way that favors its accumulation during summertime and increases its release during winter, reducing the annual discharge amplitude of the river.

b. Relationships between river discharges and rainfall anomalies

Cross-correlation coefficients were calculated to identify the lag time between rainfall anomalies in the Paraná, Iguazú, and Paraguay basins and discharge anomalies at different stations on these rivers. Series of spatially average rainfall anomalies for the period 1956–81 were calculated for each of the following regions: the Iguazú River basin, the upper and middle basins of the Paraná River, and the lower Paraguay River basin. Because there is only one rainfall series available in the upper Paraguay basin, the cross-correlation coefficient for this basin was calculated using the anomaly series of D_j for that basin for the period 1979–89. This option is supported by the fact that, in the other regions, the cross-correlation functions of D_j and rainfall anomalies with discharges take close values and similar form, as shown in Table 1.

The cross-correlation coefficients between Posadas discharge anomalies and convection anomalies in the

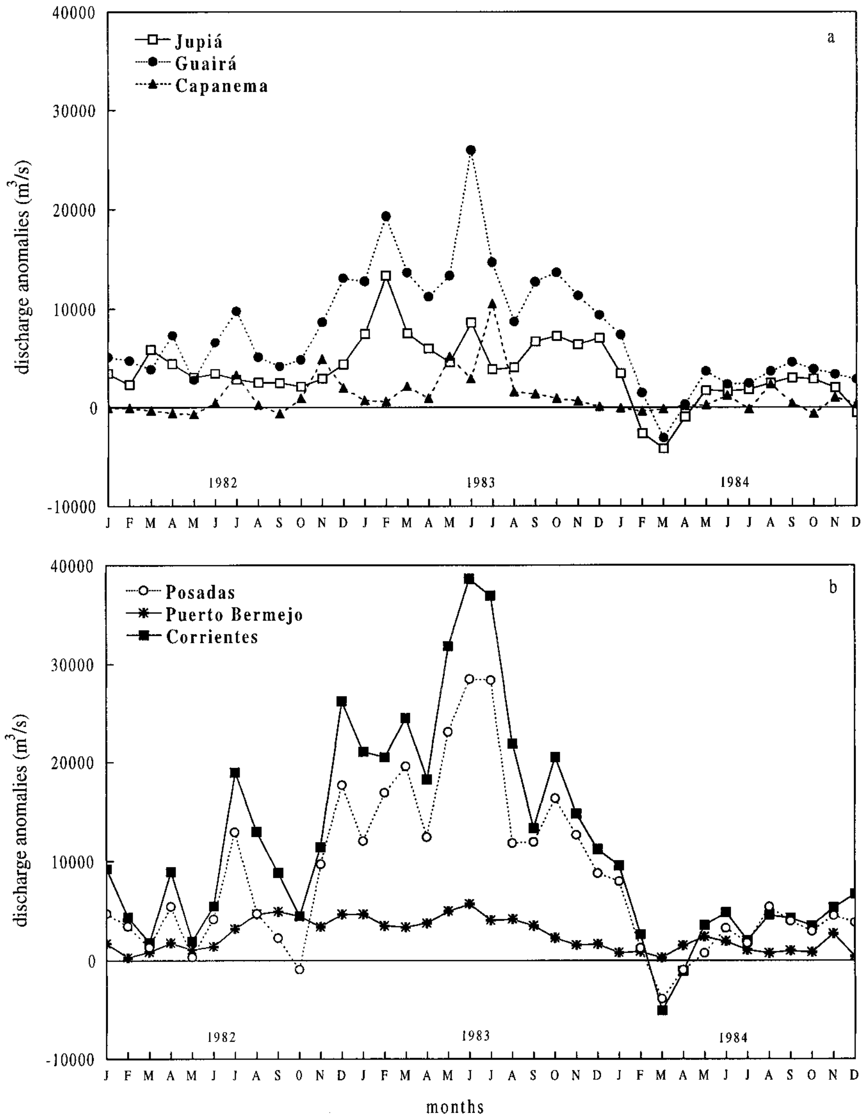

FIG. 5. Discharge anomalies in the Paraná river and tributaries for the period 1982–84.

Iguazú, middle Paraná, and upper Paraná basins are indicative of the time it takes the runoff to reach the gauging stations (Fig. 4a). For the Iguazú and the middle Paraná basins this delay is of only one month or even less, because of both the small size of the basin and the steep terrain in the Iguazú case, and the position of Posadas in the basin in the second case. For the upper Paraná basin, the delay seems to be one or two months. The correlation coefficients decrease slowly with time, remaining relatively high and positive for many months. This is an indication that part of the runoff takes a longer time to reach the river.

Figure 4b shows the cross-correlation coefficients between Puerto Bermejo discharge anomalies and rainfall anomalies in the upper and lower Paraguay basins. The delay in the lower Paraguay basin ranges from one to two months, but that of the upper Paraguay basin is longer (5–8 months), as a result of the topographical characteristics of this basin, which includes the huge flat region of El Pantanal.

In both Figs. 4a and 4b, the cross-correlation coefficients are all positive up to one year. Although most of these correlation coefficients are not significant, they suggest a low-frequency process, such as a rainfall trend, over the whole region.

4. The 1982–83 flooding event

Downstream from Corrientes, the lower Paraná River runs over Argentine territory and presents low margins and deltas in most of its 1000-km length. These features favor the flooding of large areas. As explained previously, there are no significant contributions from tributaries in this part of the Paraná River. Hence, floods

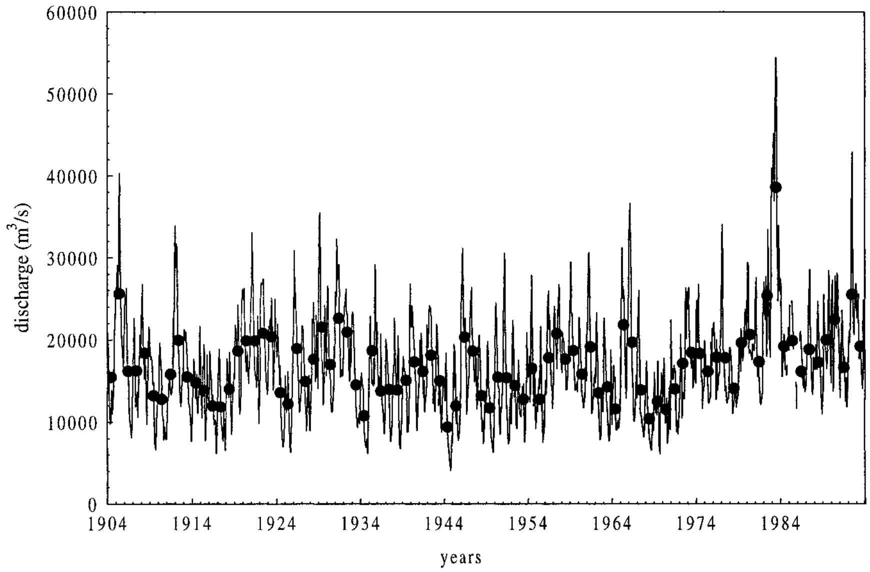

FIG. 6. Monthly (solid line) and annual (dots) Paraná river discharge at Corrientes (1904–93).

usually originate whenever exceptional streamflows occur upstream from Corrientes, as was the case in the 1982–83 flood.

Figure 5 shows discharge anomalies for the period 1982–84 relative to 1931–80 at Jupiá, Guairá, and Capanema (Fig. 5a), and Posadas, Corrientes, and Puerto Bermejo (Fig. 5b). These figures also provide insight into the relevance of the Iguazú and Paraguay rivers during the 1982–83 floods of the Paraná River in Argentina. In July 1982, discharge anomalies at Posadas were 12 000 $m^3\ s^{-1}$ as a result of positive anomalous discharge both upstream from Posadas in the Paraná River (Guairá, 9000 $m^3\ s^{-1}$) and in the Iguazú River (Capanema, 3000 $m^3\ s^{-1}$). These values were exceeded in November 1982 when the discharge at Capanema was even larger (~5000 $m^3\ s^{-1}$), contributing to an important discharge anomaly (18 000 $m^3\ s^{-1}$) at Posadas in December 1982. The largest positive discharge anomalies at Jupiá (~13 000 $m^3\ s^{-1}$) occurred in February 1983. The largest discharge anomalies observed at Posadas reached 29 000 $m^3\ s^{-1}$ in June and July, as a result of a high anomaly in Guairá (~26 000 $m^3\ s^{-1}$ in June) and in Capanema (~10 000 $m^3\ s^{-1}$ in July). The latter two represented, respectively, more than 3 and 7 times the mean historical values (see Fig. 2). Because the anomaly discharge at Jupia remained below 9000 $m^3\ s^{-1}$ during April–June, the bulk of this peak originated in the middle Paraná and Iguazú basins. It is important to underline that these streamflow anomalies were considerably higher than the effect introduced by the operation of dams on the annual cycle (Fig. 2). Figure 5 also shows that the streamflow in Posadas rapidly reflected the discharge variations in the Iguazú River and that the record streamflow of 1982–83 started upstream from Posadas.

The contribution of the Paraguay River to the 1982–83 lower Paraná basin floods started in July 1982 (Fig. 5b). During that month, there was a large peak (~20 000 $m^3\ s^{-1}$) in the discharge anomalies in Corrientes, below the confluence of the Paraguay and Paraná Rivers. This peak was caused predominantly by the middle Paraná peak but was reinforced by the contribution from the Paraguay. The same occurred once again in December 1982, when the anomalous streamflow at Corrientes exceeded 25 000 $m^3\ s^{-1}$. The maximum anomaly at this station was observed in June 1983 (~38 000 $m^3\ s^{-1}$) concurrently with the largest peaks in the discharge anomalies in Posadas (~29 000 $m^3\ s^{-1}$) and Puerto Bermejo (~6000 $m^3\ s^{-1}$). This discharge was the highest monthly discharge in the entire record of Corrientes since it first began in 1904 (Fig. 6). Accordingly, the largest flood of the twentieth century on the lower Paraná River occurred during the following months.

To summarize, the 1983 flood event in the Paraná River was the consequence of extremely high positive anomalous streamflows, not only in the upper and middle Paraná River but also in the Iguazú and Paraguay Rivers. Also, the 1983 mean discharge at Corrientes was the highest annual discharge ever recorded. In the next sections, whether these features can be attributed to the very strong EN 1982–83 episode will be discussed, with special attention to the possible causes of the extremely high streamflows observed during May–July 1983.

5. Dependence of convective activity on EN

To explore the relation between convective activity in the Paraná basin and ENSO events, monthly linear correlation coefficients between SST in EN regions and the average of D_j over each subbasin were calculated. Previously, SSTs were passed through a five-month running mean to reduce data noise and to filter short time fluctuations.

Grimm et al. (2000) studied the effect of EN events on rainfall in southern South America. They found that the most significant signals over the Paraná basin start in November of the first calendar year of the EN event, henceforth referred to as November0, with some gap during the austral summer, and end in July of the second calendar year of the same event, hereinafter July+ for short. Therefore, the correlation coefficients were calculated for each month of the period November–July. Because of data constraints, correlations were computed for the 1974–94 period, excluding the November 1982–July 1983 months, because the results will be used to discuss the 1982–83 case (Table 2).

The italicized lines in Table 2 identify months for which there is high correlation between SST in EN regions and convection. Notice that for most months of the period November–July there is a response in the upper and middle Paraná basins and in the Iguazú basins to the tropical Pacific SST anomalies. This response is weaker in the case of the Paraguay basin. According to Table 2, convection in the upper and middle Paraná and Iguazú basins is related in statistical terms to SST in the Niño-1+2 and Niño-3 regions; correlations between convection anomalies and SST in the Niño-3.4 and Niño-4 regions are lower, and the significant cases are less frequent. There are no significant correlations between SST anomalies in EN regions and convection anomalies in February and March. The highest responses to SST in the EN regions are in May in the three basins, and this response remains important until June in the Iguazú basin.

Convection in the Paraguay basin is less related to SST in the EN regions. Significant correlations are found only in January in the case of both the upper and the lower basins and in May in the case of the lower basin.

According to the runoff lag times previously discussed and to these correlations, the higher response to the SST in EN regions should be expected in Posadas streamflow during December0 to February+ and May+ to July+. The significant positive correlation of the upper Paraguay convection in January+ and of the lower Paraguay convection in May+ contribute to increase the streamflow response in Corrientes during May+ to July+. Another conclusion is that the teleconnection between SST and the convective activity in the upper and middle Paraná basins during the EN events seems to have its maximum somewhere between the Niño-1+2 and Niño-3 regions.

Lagged correlations, with SST ahead up to three months, were also calculated but are not presented because they are approximately similar to those of Table 3. Correlation between convection during November–January is greater at lag 3 in the Niño-3.4 and Niño-4 regions than at lag 0, probably as a consequence of the frequent displacement of the EN signal to the east during year 0 of the event. It is interesting to note that correlations between convection and EN SST at any lag time remain small, and even negative, during February and March.

TABLE 2. Linear correlation coefficients between five-month moving-average SST anomalies for Niño regions and D_j anomalies for different subbasins. Significant correlation coefficients for 95% confidence level are boldface. Italicized months have a high correlation between EN events and convection anomalies.

Subbasin	Month	Niño-1 + 2	Niño-3	Niño-3.4	Niño-4
Upper Paraná	Nov	0.13	0.01	0.07	0.05
	Dec	**0.62**	0.48	0.37	0.27
	Jan	**0.63**	**0.64**	**0.56**	0.46
	Feb	0.05	−0.09	−0.13	−0.12
	Mar	0.11	0.30	0.30	0.26
	Apr	0.35	0.36	0.39	0.37
	May	**0.71**	**0.54**	0.42	0.26
	Jun	0.09	0.22	0.30	0.36
	Jul	0.22	0.28	0.18	0.17
Middle Paraná	*Nov*	**0.55**	**0.55**	**0.50**	**0.53**
	Dec	0.45	0.36	0.26	0.15
	Jan	**0.54**	0.33	0.21	−0.02
	Feb	0.08	−0.04	−0.16	−0.23
	Mar	−0.25	0.12	0.06	−0.04
	Apr	0.44	0.42	0.38	0.29
	May	**0.69**	**0.67**	**0.61**	**0.53**
	Jun	0.30	0.44	0.46	0.43
	Jul	0.44	0.45	0.44	0.47
Iguazú	*Nov*	**0.53**	**0.55**	**0.52**	**0.55**
	Dec	0.45	0.39	0.29	0.17
	Jan	0.25	0.04	−0.05	−0.20
	Feb	0.23	0.12	−0.03	−0.15
	Mar	0.08	0.21	0.14	−0.13
	Apr	**0.49**	0.41	0.35	0.25
	May	**0.68**	**0.64**	**0.58**	**0.53**
	Jun	**0.57**	**0.52**	0.42	0.35
	Jul	**0.52**	**0.51**	0.44	0.41
Upper Paraguay	Nov	0.24	0.13	0.17	0.18
	Dec	0.10	0.00	−0.06	0.03
	Jan	0.48	0.35	0.28	0.30
	Feb	−0.04	−0.11	−0.18	−0.13
	Mar	−0.37	0.03	0.03	0.11
	Apr	−0.49	−0.24	−0.24	−0.17
	May	0.29	0.41	0.44	0.37
	Jun	−0.21	0.17	0.29	0.34
	Jul	−0.35	−0.22	−0.09	0.04
Lower Paraguay	*Nov*	0.25	0.33	0.46	0.46
	Dec	0.32	0.25	0.14	0.14
	Jan	**0.56**	0.38	0.31	0.31
	Feb	−0.22	−0.35	−0.47	−0.47
	Mar	−0.28	0.16	0.12	0.12
	Apr	0.02	0.11	0.09	0.09
	May	**0.55**	**0.63**	**0.63**	**0.63**
	Jun	0.21	0.30	0.26	0.26
	Jul	0.24	0.19	0.20	0.20

Figure 7 shows SST anomalies of the Niño-1+2 and Niño-3 regions for the 1982–83 and 1997–98 events. Leaving the 1997–98 case for later discussion, it may be noticed that the 1982–83 event has its maximum strength in the Niño-1+2 region during April–August 1983; the Niño-3 region remains very warm during these same months. These features, coupled with the high

Table 3. SST anomalies (°C) in the tropical Pacific Niño regions and monthly mean discharge anomalies ($m^3 s^{-1}$) at Corrientes and Posadas during EN events. EN years were selected according to Kiladis and Diaz (1989). SST anomalies indicated in brackets were obtained from NOAA's Climate Prediction Center and were included for comparison with the 1997 EN event. Maximum discharge anomalies observed during Jan0–Dec+ are shown.

EN year0	Niño-1 + 2 Apr+ to Jun+	Niño-3 Apr+ to Jun+	Corrientes discharge anomaly May+ to Jul+	Max discharge anomaly at Corrientes (month)	Posadas discharge anomaly May+ to Jul+	Max discharge anomaly at Posadas (month)
1904	0.80	0.87	16 465	22 671 (Jun+)	14 318	20 350 (May+)
1911	−0.27	0.13	−571	15 393 (Jan+)	−328	11 218 (Dec0)
1913	−0.57	0.13	−2737	6194 (Dec+)	−1884	2339 (Jan0)
1918	0.10	0.20	4620	6600 (Jun+)	1535	6723 (Nov+)
1923	−1.60	−0.30	−1878	10 304 (Nov0)	−661	8798 (Jun0)
1925	0.00	0.47	3540	9675 (Feb+)	3308	8836 (Apr+)
1930	−0.27	0.57	9998	11 566 (May+)	5841	10 177 (Mar+)
1932	−0.60	−0.40	−3960	6864 (Apr0)	−3574	6312 (Apr0)
1939	0.20	0.17	1649	11 329 (Dec0)	−1140	8137 (Dec0)
1951	−0.37	0.00	−3518	9430 (Mar0)	−3124	8314 (Mar0)
1953	−2.00	−0.53	6349	10 195 (Jun+)	4578	6955 (Jun+)
1963	−1.33	−0.73	−5361	4125 (Nov0)	−3168	5199 (Nov0)
1965	−0.93	0.13	−1640	15 509 (Mar+)	−977	9177 (Dec 0)
1969	−0.77	−0.20	−6039	−204 (Jun0)	−1839	2378 (Nov0)
1972	−0.70	−0.50	433	12 025 (Oct0)	1377	12 198 (Oct0)
1976	0.03	0.17	−2290	12 840 (Feb+)	−1336	9500 (Feb+)
1982	(4.45) 3.57	(2.06) 1.47	34 215	37 853 (Jun+)	25 718	28 561 (Jun+)
1986	(1.67) 1.57	(1.39) 0.83	8560	10 885 (Jun+)	6914	9755 (May+)
1991	(1.97) 1.23	(1.18) 1.20	17 821	25 305 (Jun+)	11 797	14 963 (Jun+)
1997	(3.31)	(0.99)	11 929	23 258 (May+)	7156	14 819 (Apr+)

response of the middle Paraná and of the Corrientes streamflows during May+ to July+ to EN SST, are consistent with the maximum discharges registered during these months of 1983 (Fig. 5).

6. Streamflows during EN events prior to 1980

The previous section identified teleconnections between SST in EN regions and convective activity. Then, it is pertinent to show that the April+ to June+ teleconnections with convection are actually transferred to the river streamflow.

The exceptionally high streamflows of 1983 allow us to reach conclusions, even using the regulated discharges. In fact, the total storage capacity of the dams upstream of Posadas was about 200 000 hm^3 in 1983, including 29 000 hm^3 of Itaipú; the anomaly discharge at Posadas exceeded 200 000 hm^3 in May–July 1983 and

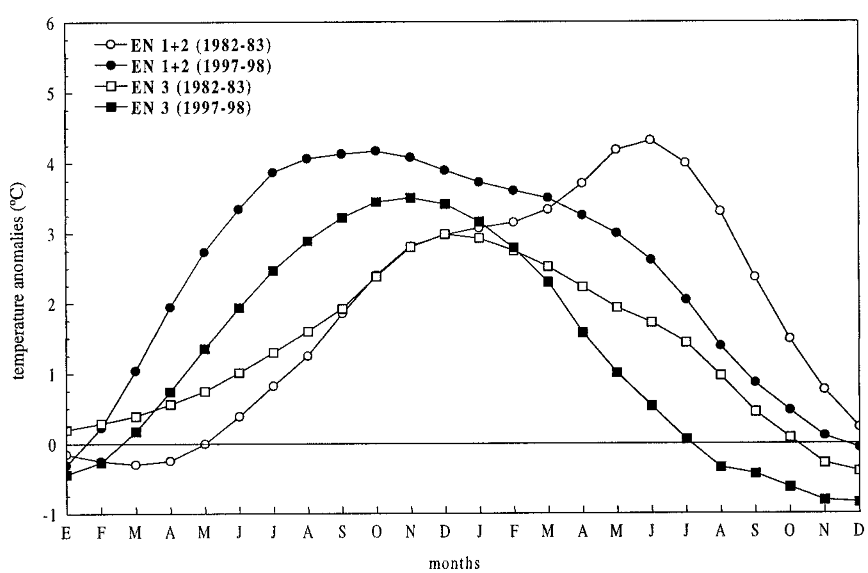

Fig. 7. Five-month running-mean SST anomalies in regions Niño-1+2 (circles) and Niño-3 (squares) for EN events 1982–83 (open) and 1997–98 (filled) (data from NOAA's Climate Prediction Center).

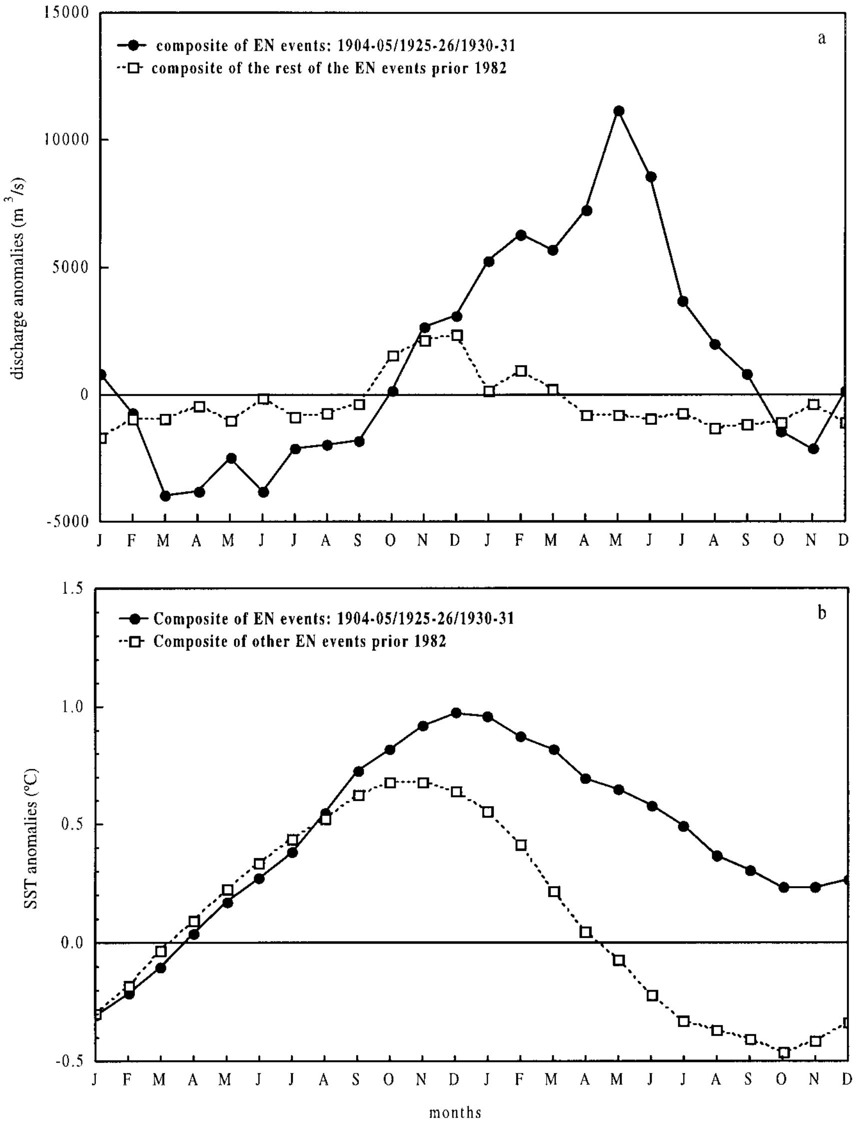

FIG. 8. Composites of (a) discharge anomalies at Posadas and (b) SST anomalies in Niño-3 for the EN events of 1904–05, 1925–26, and 1930–31 and for the other EN events prior to 1982.

was about 150 000 hm^3 in December 1982–March 1983. When these anomalies are compared with the average change introduced by the dams, it is clear that they cannot have an important percentage change with respect to the unregulated discharge (Fig. 2). This is not the case with the other EN events during which the discharge anomalies were not so extremely high, however. For this reason, the analysis was restricted to the 16 EN episodes that took place in the 1904–76 period.

Table 3 shows SST anomalies of the Niño-1+2 and Niño-3 regions during the April+ to June+ period for all of the events since 1904. Since 1982, the EN events persisted during this trimester more frequently than before. This result is also true for the Niño-3.4 and Niño-4 regions (not shown) and for another dataset (the Coupled Ocean–Atmosphere Dataset). Hence, it appears that this change was real and not caused by data flaws. Yet, because this finding is not the focus of the current paper, it will not be discussed further.

Except for the 1904 episode, there was no other case before 1982 with an anomaly of at least 0.4°C in the Niño-1+2 region. As a matter of fact, in most of the cases, the SST anomaly was negative in this region. Therefore, we selected the three cases in which the SST anomaly was higher than 0.4°C in the Niño-3 region, namely, the 1904–05, 1925–26, and 1930–31 events. The composite of these three cases, both in the SST at Niño-3 region and in the discharge at Posadas, as well as of the other 13 cases, is presented in Fig. 8a. No other discharge is shown, because, with the exception of the Corrientes record, the Posadas record is the only one starting before 1904. The Corrientes discharge com-

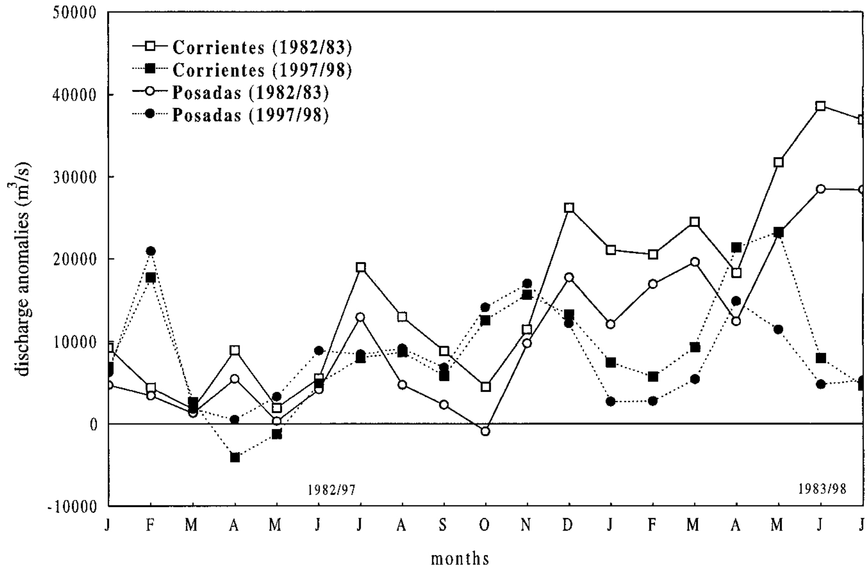

FIG. 9. Comparison of discharge anomalies in Posadas and Corrientes during the 1982–83 and 1997–98 EN events.

posite (not shown) is similar to that of Posadas and does not add substantial information, aside from a considerable increment in the May+ anomaly of 3000 $m^3 s^{-1}$ with respect to Posadas that should be attributed to the Paraguay response, which is consistent with this river's contribution described in section 5. Figure 8b shows that, in the Niño-3 region, the three EN episodes that lasted until the austral autumn+ were also, in the average, more intense at their summit than were the rest of the cases. During April+ to June+ the difference in the SST between the two composites is 0.7°C, which is a considerable signal according to this EN SST variability. The corresponding discharge anomalies in each of these three cases at Posadas and Corrientes are consistent with the Niño-3 signal and with the convection response discussed in the previous section. The peak anomalies in the three cases rank accordingly with the corresponding rank of the SST anomaly at the Niño-3 region. For the 16 events of the 1904–76 period, this relationship generally holds, as shown from the Spearman rank correlation coefficients calculated between the average discharge during April+ to July+ and Niño-3 SST. In the case of Corrientes, this coefficient is 0.69; for Posadas it is 0.51, both being significant at the 95% level.

Table 3 also shows the maximum monthly discharge of each event together with its respective month. In Posadas, not only do the three above-mentioned events have their maxima in April+ to July+, but also, of the 13 remaining events, only one (1953) had its peak during this period. In the case of Corrientes, the streamflow peaks were in June 1905 and in May 1931, but in 1926 the peak was in February, and two of the remaining events had their peaks in the May+ to July+ period. This result indicates that the Niño-3 signal is more consistent in the middle Paraná (Posadas) than in the Paraguay data (Corrientes includes the Paraguay contribution), in agreement with the convection response shown in section 5. The average of the monthly anomaly peak of the 1904–05, 1925–26, and 1930–31 events in Posadas was 13 120 $m^3 s^{-1}$, considerably greater than 7500 $m^3 s^{-1}$, the corresponding average of the other 13 cases, the difference being significant at the 90% level. In the case of Corrientes, the respective averages were 14 600 and 9000 $m^3 s^{-1}$, but the difference does not reach the 90% level of significance. Both differences indicate that events persisting until the austral autumn+ are associated with greater peaks in the Paraná River streamflow. This result was obtained even without considering the exceptional case of 1982–83, which obviously would strengthen the same conclusion.

The outcome of this section constitutes new evidence that there is a teleconnection between SST in the Niño-3 region and the middle Paraná streamflow, which in the case of large positive SST anomalies results in very high discharges in this river.

7. Comparison between the 1982–83 and 1997–98 EN events

During the three EN events after 1983, the streamflow anomalies at the middle Paraná were also very high in the May+ to July+ period. For instance, the discharge in Corrientes in June 1992 was 25 300 $m^3 s^{-1}$, the second largest monthly value in the entire record, which was also the case for the SST anomaly in the Niño-3 region. However, because after 1980 the river was regulated by numerous dams, these cases will not be discussed, with the exception of the 1997–98 event, which is interesting for understanding the possible influence

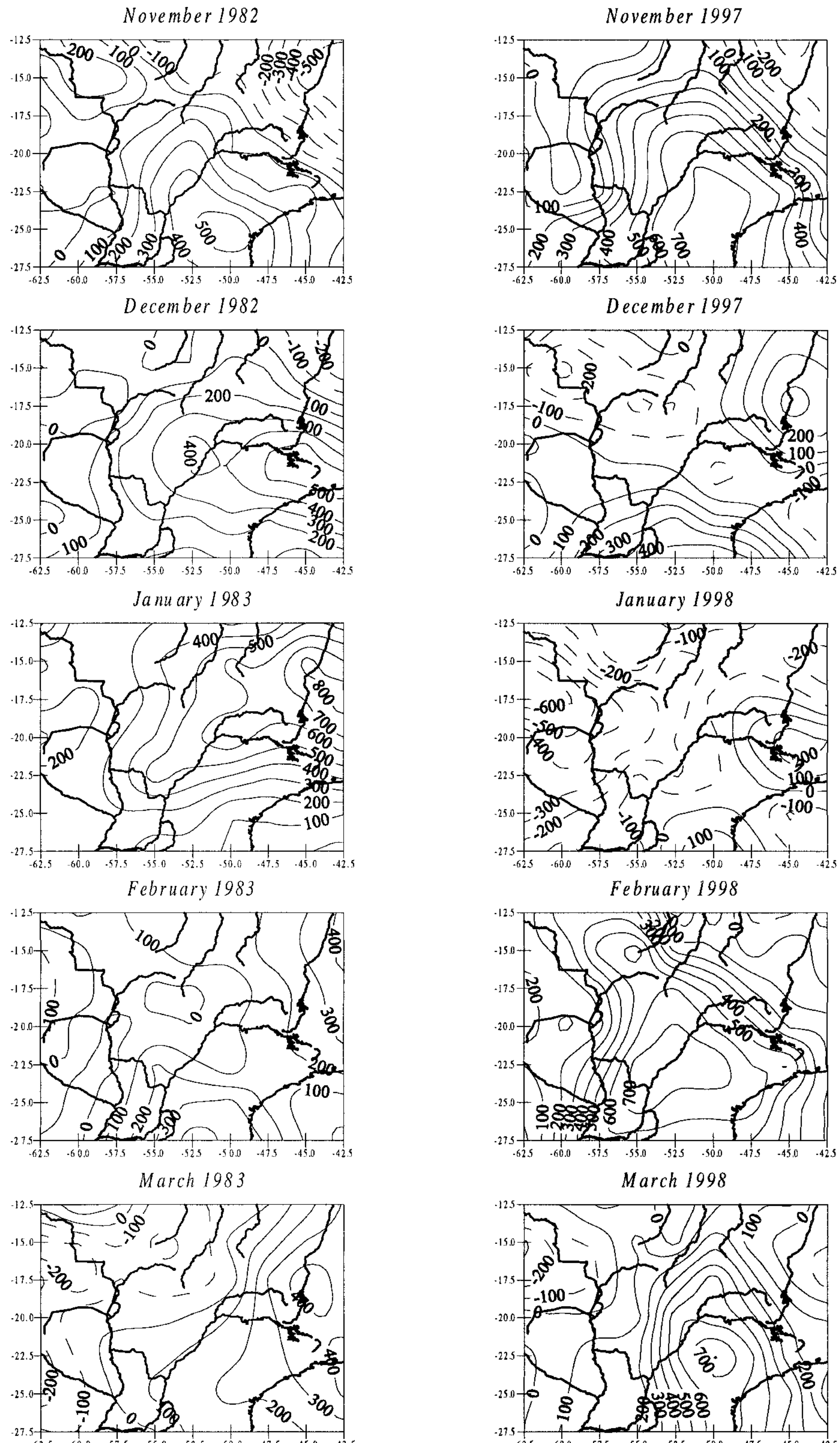

FIG. 10. The D_j anomalies for the periods Nov0–Jul+ of the EN events 1982–83 and 1997–98.

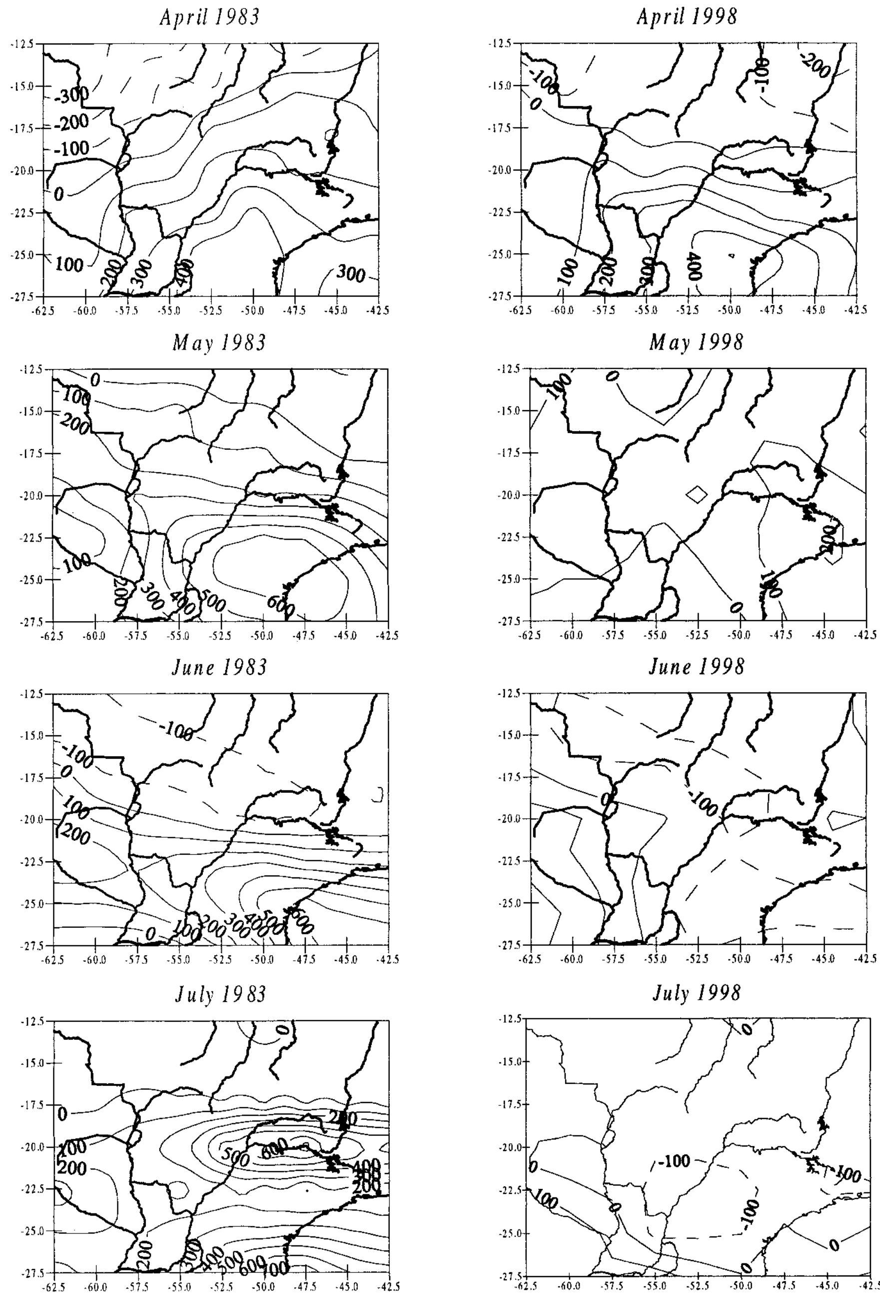

Fig. 10. (*Continued*)

of the SST anomalies of the neighboring Atlantic Ocean on the Paraná streamflow during the summer.

The 1997–98 EN was one of the strongest EN events of the twentieth century. In 1997 and the first months of 1998, positive SST anomalies in the Niño-3 and Niño-1+2 regions even surpassed the 1982–83 anomalies (Fig. 7). The event persisted well into the year+ but was somewhat atypical in the sense that the Niño-1+2 region in April–June 1998 remained very warm, but this warming was not so important in the other EN regions. Figure 7 shows that in the Niño-3 region the positive anomaly had almost vanished by June 1998 while it was still very strong in the Niño-1+2 region.

Figure 9 presents a comparison of discharge anomalies in Posadas and Corrientes during the 1982–83 and 1997–98 EN events, for the period between January and July. Discharges at Puerto Bermejo are not presented because they were similar during both events. The main differences were observed during January+ to March+ and June+ to July+, for which the 1982–83 discharge anomalies were substantially higher. However, by 1997 the reservoir capacity upstream of Posadas increased to

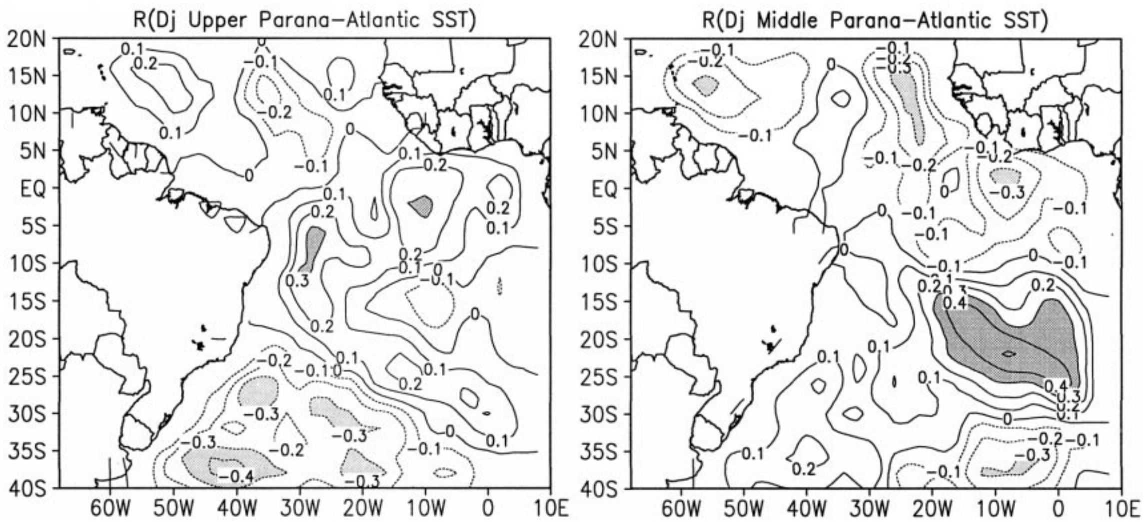

FIG. 11. Correlation fields between D_j anomalies for the (left) upper and (right) middle Paraná basins and Atlantic SST for Jan.

256 000 hm^3, and the river was intensely regulated. Therefore, to elude this problem, the comparison between these events was carried out in the OLR field, as an independent proxy for streamflow.

The convection anomalies for each month of the period November0 to July+ of the 1982–83 and 1997–98 EN events are presented in Fig. 10. During 1982–83 and 1997–98, the greatest positive anomalies of D_j occurred in the Atlantic coastal region. Differences between the two events are evident for the period May+ to July, when there were intense convection anomalies in the Iguazú and part of the middle Paraná basins during May–June 1983 and in the upper Paraná and Iguazú basins in July 1983. On the contrary, during May–July 1998 the convection anomalies were much smaller, and even negative, over those regions. This result indicates that the SST in the Niño-3 region rather than in the Niño-1+2 region may be decisive in the convection over those subbasins, reinforcing the same conclusion obtained in section 6.

From the analysis of Figs. 5 and 10, it can be appreciated that the large positive convection anomalies observed in November–December 1982 in the middle and upper Paraná and the Iguazú basins were reflected in the discharge observed at Corrientes and Posadas from December 1982 onward. This result is consistent with the zero to two-month delay between rainfall in those basins and discharge anomalies in Posadas (Fig. 4a). The secondary peak in the Paraná River discharge, observed in March 1983 (Fig. 5a), is a consequence of positive convection anomalies in the upper Paraná basin during January 1983 and in the middle Paraná basin during February and March 1983 (Fig. 10). The maximum positive discharge anomalies observed during May–July 1983 were also related to positive convection anomalies during April–July 1983 in the upper Paraná, middle Paraná, and Iguazú basins. The large positive anomalies in the Iguazú basin during June–July 1983 were followed by a maximum discharge anomaly in Capanema, on the Iguazú, during July 1983. Discharge anomalies in the Paraguay River were positive during the period November 1982–July 1983. They resulted from positive convection anomalies over the lower Paraguay consistent with the one–two-month delay between rainfall and discharge anomalies (Fig. 4b). The peak observed in Puerto Bermejo during July 1983 was due to positive convection anomalies in both the lower Paraguay basin during May–July 1983 and the upper Paraguay basin during November 1982–January 1983. The preceding analysis not only shows the agreement between convective and river discharge anomalies for that particular case but also indicates that convection could be used as proxy data for the more general features of the streamflow in the Paraná basin north of 22°S, at least in the case of strong anomalies.

The analysis of the 1997–98 event shows that dams effectively modulated the Paraná River response to convective anomalies (Figs. 9 and 10). For example, during February–March 1998, convection anomalies in the upper and middle Paraná basins were greater than those occurring during the same period of 1983, but they were not reflected in the discharge anomalies until April (Fig. 9). The April–May 1998 peak in the discharge anomalies may reflect the enhanced release of water accumulated in the dams from the positive rainfall anomalies in the previous months, as well as the convection anomalies during April in the region southward of 20°S (Fig. 10).

The convective activity over the middle Paraná and its tributaries was substantially higher during December 1982–January 1983 and May–July of 1983 than during the equivalent months of the 1997–98 event. Although

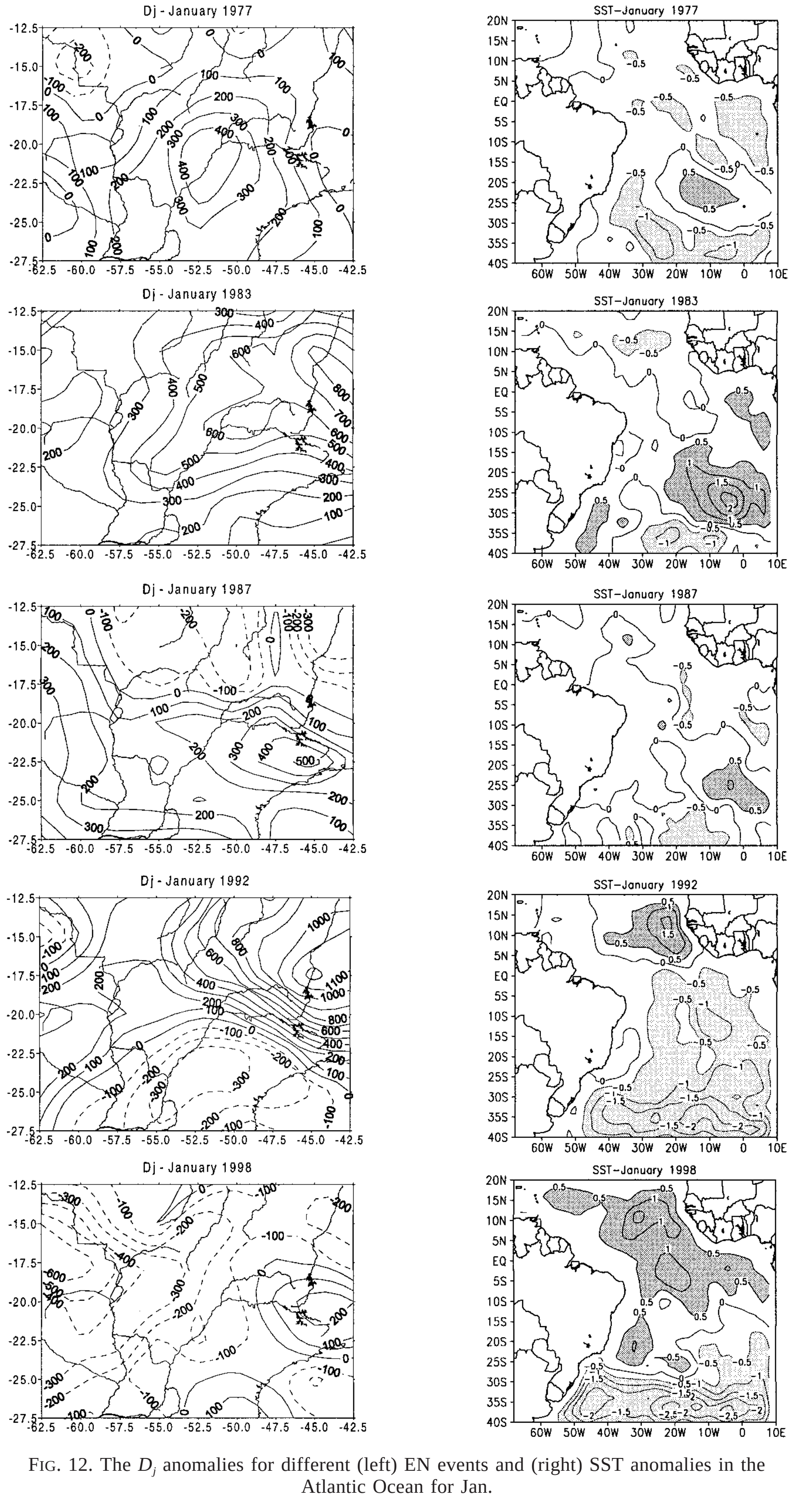

FIG. 12. The D_j anomalies for different (left) EN events and (right) SST anomalies in the Atlantic Ocean for Jan.

for the May–July period this difference can be attributed to the 1983 SST warming of the Niño-3 region that persisted longer than in 1998, for the southern summer months the difference probably is not related to the EN SSTs, because the warming of the Niño-1+2 and Niño-3 regions was similar in both events (Fig. 7). For this reason, it is meaningful to explore the possible SST influence of the contiguous Atlantic at this time of the year.

8. Dependence of convective activity on Atlantic SST

The major convective differences between the two events during the austral summer occurred in January. Hence, the January correlation between the OLR indexes averaged over the upper and middle Paraná basins and the Atlantic Ocean SST was calculated for the 1974–94 period to explore whether the Atlantic SST can provide an explanation of the observed difference between the 1983 and 1998 convective activity. For this same reason, January 1983 was excluded in the correlation calculation.

Figure 11a shows the correlation field for January between convection anomalies in the upper Paraná basin and SST anomalies in the Atlantic. This figure indicates that positive (negative) convection anomalies predominate in the upper Paraná basin when there is a pattern defined by cold (warm) SST from the SACZ to the south and warm (cold) SST to the north of the SACZ. Because we are using the SACZ as geographical reference, it is pertinent to indicate that the SACZ latitude at the coast is about 23°S, and that it extends into the ocean toward the southeast. The above-mentioned relationship between SST and convection might be caused by the enhancement of the SACZ provoked by this SST pattern (Barros et al. 1999). Figure 11b corresponds to the correlation field with the convection in the middle Paraná basin. In this case, there is a wide region with significant positive correlation east of 20°W, at the 10°–30°S latitude band.

Figure 12 shows the convective and the Atlantic SST anomalies for January+ corresponding to all EN events with available OLR data. During January 1983, there was an SST field with warm waters to the north of the SACZ, especially west of 20°W, and cold waters to the south, except near the coast. Similar patterns were also observed in January 1977 and January 1987. According to the correlation fields, this SST pattern tends to be accompanied by convection over the upper and middle Paraná basins, as was exactly the case in these three events. On the other hand, during January 1998 there was a pattern of positive SST anomalies north of the SACZ and strong negative SST anomalies to the south. According to the correlation field, this pattern favors positive convective anomalies over the upper Paraná basin, but because the region surrounding 20°S, 10°W had negative SST anomalies, negative convective anomalies were more probably expected over the middle Paraná basin. This anomaly pattern in the convection field, positive over the upper Paraná and negative over the middle Paraná basins, was precisely that observed in January 1998. The January 1987 SST pattern is similar to that of 1998, except that the warm water to the north of the SACZ is considerably reduced. Again, the convective field had positive anomalies over the upper Paraná basin and negative ones over the middle Paraná basin.

It is evident that the Atlantic SST field may influence the convection over the upper and middle Paraná basins in January. Consequently, the differences between the 1983 and 1998 discharges for the periods January–March should be attributed, at least partially, to the opposite-in-sign SST anomaly east of 20°W at the 10°–30°S latitude band.

Note that, during April–July (the months with maximum streamflow response to the Niño-3 region), the linear correlation fields between Atlantic SST and convection anomalies (not shown) do not indicate significant correlations. The five events presented in Fig. 12 had negative SST anomalies south of the SACZ, indicating that some possible relationship of the EN events with the South Atlantic SST cannot be discarded. If such were the case, the common feature in the convection field, specifically the positive anomalies over the Upper Paraná basin convection, could be caused directly by an atmospheric teleconnection with the Pacific SST, instead of being caused by the Atlantic SST.

9. Summary and concluding remarks

Convection over the Iguazú, upper Paraná, and middle Paraná basins is significantly correlated with the Niño-1+2 and Niño-3 SST from November to June, with a gap in February–March. The convection over the middle Paraná and Iguazú basins has the highest correlation with EN SST in May. According to this convection response to the EN SST, the discharge peak at the river should be expected after May. In fact, the middle Paraná maximum streamflow anomalies during the 1983 event occurred in May–July, as happened in all the other events with SST anomalies larger than 0.4°C in the Niño-3 region during April+ to June+, except in the 1997–98 and 1925–26 cases, when the peak was observed earlier.

The peak discharge at the middle Paraná basin is clearly related to the Niño-3 SST anomaly magnitude. The strongest anomaly in both the Niño-3 SST and in the streamflow occurred in 1983. Likewise, the other strongest anomalies in the Niño-3 SST, in 1992 and 1905, were accompanied by the other highest streamflows of the entire record. The Niño-3 SST corresponding to events of a period before the regulation of the river, namely, 1904–76, have significant correlation in rank with discharges at Corrientes and Posadas, indicating that there is a bias to increasing peak discharge with increasing Niño-3 SST.

Despite the high correlation between convection and Niño-1+2 SST, the influence of these SST on the middle Paraná basin does not seem to be decisive. This finding results from the inspection of the 1925–26, 1930–31, and 1997–98 events. In the first two cases, the Niño-1+2 SST anomaly was not even positive during April+ to June+, and still there were important positive discharge anomalies in both cases. The 1997–98 case is even more illustrative. Figure 7 indicates that, while the warming at the Niño-3 region was vanishing in May–June, positive anomalies were still important in the Niño-1+2 region. However, convective anomalies during these months were weak and even mostly negative in the upper and middle Paraná basins (Fig. 10). These three cases show that the high correlation between Niño-1+2 SST and convection on the Paraná basin during April+–June+ could be more the consequence of the correlation between the Niño-1+2 and Niño-3 SSTs than the result of a direct link.

As a result of the previous considerations, great discharges in the middle Paraná basin during EN events should occur in May+ to July+ whenever there is an important positive anomaly in the Niño-3 region during April+ to June+. The magnitude of these discharges tends to increase with greater SST anomalies. In agreement with this result, the exceptional streamflow of the middle Paraná basin during May–July 1983 was consistent with the exceptional SST anomaly observed in the Niño-3 region during April–June 1983.

During the first months of 1983, positive and large streamflow anomalies, which possibly were related to the SST observed in January, were also recorded in the Paraná River. In fact, an SST anomaly pattern in the South Atlantic during January, with warm (cold) water to the north of the SACZ and cold (warm) water to the south, is associated with increased (decreased) convection over the upper Paraná basin. Positive (negative) SST anomalies west of 20°W are also statistically associated with positive (negative) convective anomalies in the middle Paraná basin. According to these relationships and the SST January 1983 pattern, an increased convection over both basins was probable and in fact occurred, contributing to prolong the secondary discharge peak of this event.

The May–July 1983 streamflow in the middle Paraná River was the highest of the last century. It was principally the consequence of extremely high positive convective anomalies in the upper and middle Paraná basins but also of similar anomalies in the Iguazú and Paraguay basins. During the 1982–83 EN event, SST in the Niño-3 region during April+ to June+ were the highest ever observed in the instrumental record (Table 3). Because these SST have a great impact on the convection over the Iguazú and the upper and middle Paraná basins during May+ to July+, it can be concluded that the exceptional flood was principally caused by these extraordinary SST.

Note also that, for every EN event since 1976, SST anomalies in the Niño-3 region have been positive during April+ to June+, indicating some possible change in the phase of the EN events. From this new perspective, the 1983 Niño-3 SST anomaly does not seem too extraordinary. This subject deserves a careful analysis that goes beyond the scope of this paper, because, in addition to its scientific significance, it might be of enormous societal importance because of its possible impact on the Parana extreme flows.

Acknowledgments. This work was supported by University of Buenos Aires under Grant UBACYT JX084 and by IAI-CRN 055. Discharge data were taken from the Argentine Department of Water Resources.

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