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Extreme discharge events in the Paraná River and their climate forcing

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Abstract

The largest discharge anomalies of the Paraná River were examined focusing on the contribution from the sub-basins and on the climate forcing of these events. Major discharge anomalies at Corrientes originated in the central and southern Upper Paraná basin with relatively small contributions from the Paraguay river and the northern Upper Paraná basin.

About two thirds of the major discharge anomalies in Corrientes occurred during El Niño events while none was registered during La Niña events. Major discharge anomalies related to El Niño occurred either in the spring of the year of El Niño onset or in autumn of the following year (autumn (+)) accompanying the precipitation signal of El Niño in eastern subtropical South America. The signal during autumn (+) is the most relevant as five out the six top discharges of the Paraná River at Corrientes occurred in this season. The remaining third of the major discharges not related to El Niño took place during the austral spring or austral summer of neutral periods. In each of these seasons, they share a common sea surface temperature anomaly pattern in the proximity of the South American coasts.

Keywords: Flood; El Niño; Paraná; River discharge

1. Introduction

The Paraná River, the most important tributary of the Río de la Plata, has a drainage basin of 2.6×10^6 km^2 and contributes with more than 80% to Río de la Plata streamflow. It begins at the confluence of the Grande and Paranaíba rivers and its main tributaries are the Paranápanema, Iguazú, and Paraguay rivers (Fig. 1). Upstream from the confluence with the Paraguay at Corrientes, the river is known as Upper Paraná, and from this city down to 32°S as Middle Paraná. Downstream this point, it is called Lower Paraná.

The Upper Paraná flows mostly in areas with steep terrain that favors runoff (Tossini 1959) while the Middle and Lower Paraná flows in a gently sloping plain. The last river stretch becomes a delta and

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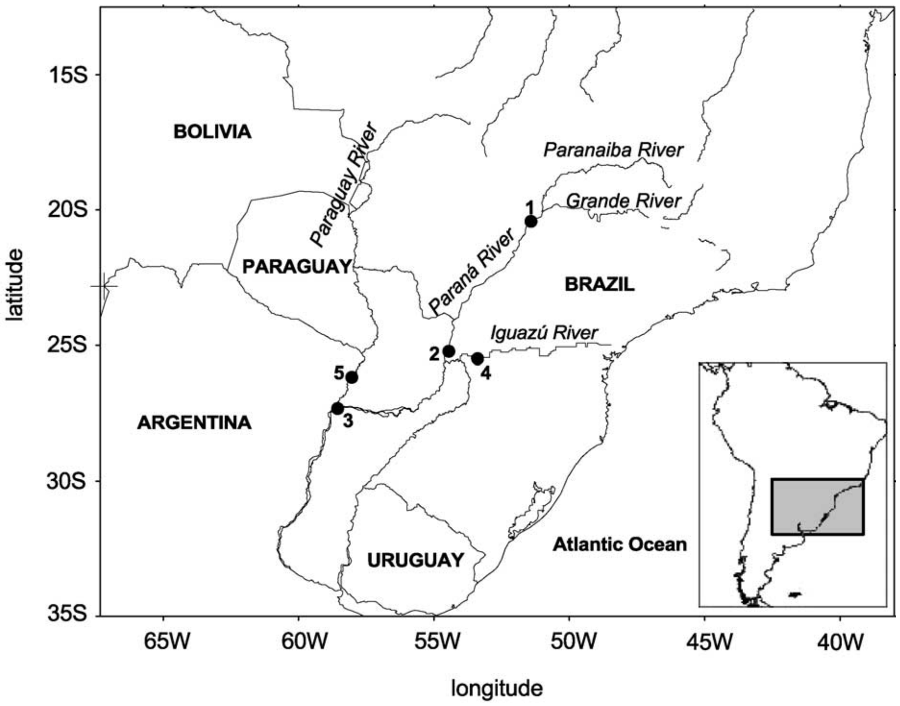

Fig. 1. Gauging stations and rivers, 1: Jupiá, 2: Itaipú, 3: Corrientes, 4: Salto Caxias and 5: Puerto Bermejo.

together with the Uruguay River forms the Río de la Plata. Large areas of land along the Middle and Lower Paraná margins are frequently subject to extended floods, which cause considerable damage. For instance, during the 1983 flood more than 100,000 people had to be evacuated (Anderson, 1993), with losses that amounted more than one billion American dollars.

The mean discharge of the Upper Paraná is about 16,000 m^3/s and only increases less than 1,000 m^3/s downstream from Corrientes (Secretaría de Energía, 1994). During the highest floods, monthly discharges at Corrientes exceed twice, and even three times, the mean discharge while, as shown by monthly data (http://www.mecon.gov.ar/hidricos/mapashidricos/mapageneral.htm), contributions from the Middle and Lower Paraná basins to extreme discharges are relatively small. The only important exception to this fact occurred during the 1998 autumn flood when the Middle Paraná had an important contribution due to extraordinary rainfalls.

Literature about the Paraná streamflows has mainly dealt with the statistical analyses of discharges, remote climate forcing, or descriptions of individual events. For instance, García and Vargas, (1996,1998); Genta et al., (1998) have identified a positive trend in the Paraná discharges and its tributaries since 1976, and Robertson and Mechoso (1998) analyzed decadal teleconnections between sea surface temperature (SST) and the Paraguay and Paraná streamflows.

Consistent evidences of the link between the Paraná discharge and the El Niño-Southern Oscillation (ENSO) have been found as well. For example, Aceituno (1988) found a weak negative correlation between discharges at Corrientes and the southern oscillation index (SOI) during November–April, and Amarasekera et al., (1997) reported a positive correlation between the annual discharge at Corrientes and the equatorial Pacific SST averaged on quarters lagging ahead of the discharge year. Depetris et al., 1996 reported a significant coherence-square between SST at the equatorial Pacific and discharge at Corrientes in the neighborhood of the 2.5 years period. They reported the extraordinary magnitude of the 1982/

1983 flood, which coincided with the strong El Niño event of 1982, and commented that four other large floods also occurred in coincidence with El Niño events. Camilloni and Barros (2000) studied the river discharges resulting from the 1982–1983 and 1997–1998 El Niño events. Robertson et al., (2001) analyzed the interannual to decadal predictability of the Paraná River extracting near-cycling components of the summer river streamflow. They found that the ENSO oscillatory component was associated to changes in the probability distribution of monthly flows and that the decadal modulation of ENSO may be important although the predictability due to ENSO at interannual lead times is small. Berri et al. (2002) showed that averaged flows observed during El Niño events are always larger than those observed during La Niña events. More details on the variability of the Río de la Plata basin climate and hydrology can be found in a recent report of the Climate Variability Program (CLIVAR) (Mechoso et al., 2001) and the references therein.

Despite the aforementioned contributions, a complete description of the highest floods and their causes is still lacking. Therefore, this article focuses on the contribution from the sub-basins upstream from Corrientes to the major discharges of the Paraná, and on the possible climate forcings of such events. Major discharges at the Middle and Lower Paraná themselves are not part of this study due to the lack of long-term series at stations downstream from Corrientes. However, since the Middle and Lower Paraná discharges are mostly determined, with a certain lag, by the Upper Paraná discharge, the conclusions are also useful for the understanding of floods in these sectors of the river.

2. Data

The study is based on monthly discharges at five gauging stations. This allows the estimate of some sub-basins contributions to the Upper Paraná River discharge (Fig. 1). Table 1 shows their record periods and average annual discharges.

Natural discharges at the Brazilian gauging stations of Jupiá, Itaipú, and Salto Caxias were obtained from the Operador Nacional do Sistema Elétrico (ONS). Data from the Argentine stations, namely Corrientes and Puerto Bermejo, were taken from the Subsecretaría de Recursos Hídricos (SRH). Puerto Bermejo discharges do not require corrections because there are no dams on the Paraguay River. On the other hand, dams upstream from Itaipú affect Corrientes streamflow. Comparison between regulated and natural monthly flows at Itaipú indicates that the regulation upstream from this location has ranged from $-7{,}000$ to $+4{,}600\ m^3/s$, being negative in summer and positive in winter and spring. However, in the case of large positive discharge anomalies, these differences were smaller, about 5%—or even less—of the Corrientes discharge anomalies, with only one exception that rose close to 10%. Downstream from Itaipú, the large dams of Itaipú and Yaciretá do not introduce important alterations in the river flow.

Monthly rainfall series were taken from a data set assembled by Willmott and Matsura (2001). These data are available in a 0.5″ 0.5° grid for the period 1950–1999. The relation between SST and river discharges was studied using the monthly SST data set GISST version 2.3b obtained from the British Atmospheric Data Centre, 2002. The starting and end months of El Niño and La Niña

Table 1
Gauging stations shown in Fig. 1. ONS: Operador Nacional do Sistema Elétrico, SRH: Subsecretaría de Recursos Hídricos

River	Station	Source	Data period	Annual mean discharge 1931–1980 ($10^3\ m^3/s$)
Paraná	Jupiá	ONS	1931–1998	5.9
Paraná	Itaipú	ONS	1931–1998	9.1
Paraná	Corrientes	SRH	1904–1998	15.9
Iguazú	Salto Caxias	ONS	1931–1998	1.2
Paraguay	Puerto Bermejo	SRH	1910–1998	3.5

events that occurred after 1950 were taken from Trenberth (1997) and ENSO events before 1950 from Kiladis and Diaz (1989).

3. Major discharge events

Table 2 shows the largest discharge anomalies at Corrientes calculated with respect to the 1931–1980 monthly mean. The sixteen events listed correspond to the 1904–2000 period, and were selected based on the criterion that their discharge anomalies were at least three times the standard deviation of the respective month. If two consecutive months met this requirement, only the one with the largest anomaly was retained. Hereinafter, these discharge anomalies will be referred to as the major discharge anomalies. The magnitude of these extraordinary discharges at Corrientes minimizes the possible impact of water management by the upstream dams.

The cases listed in Table 2 constitute events that were necessarily caused by considerable monthly precipitation anomalies over a large area of the upstream basin. Because of their size and time scale, these precipitation anomalies could be likely linked to a common large-scale climate forcing. To facilitate the discussion of this aspect, Table 2 includes a classification of the events according to the season and the phase of ENSO.

The monthly discharge anomalies at the gauging stations of Jupiá and Puerto Bermejo represent, respectively the northern Upper Paraná, and the Paraguay discharges. In the case of Jupiá, the discharge anomalies corresponding to the month before the event in Corrientes were also included due to the possibility of a zero to one-month lag in the streamflows between these stations (Camilloni and Barros 2000). Table 2 also shows the contribution from the basin corresponding to the central sector of Upper Paraná and of the Iguazú rivers, calculated by subtracting the discharges at Jupiá from the sum of the discharges at the gauging stations of Salto Caxias and Itaipú. This basin will hereinafter be referred to as the central Upper Paraná basin. Similarly, the difference between the Corrientes discharges and streamflows at Itaipú, Puerto Caxias, and Puerto Bermejo represents the contribution from the Upper Paraná basin between the confluence of the Iguazú and Paraguay rivers with the Paraná. Its respective basin will be addressed in this paper as the southern Upper Paraná basin.

Table 2
Maximum discharge anomalies at Corrientes and the corresponding discharge anomalies at Jupiá and Puerto Bermejo and discharge contribution anomalies of two sectors of the Upper Paraná. Previous month discharge or contribution anomaly is indicated in brackets. Values in 10^3 m^3/s.

Corrientes Discharge peak date		Jupiá (Northern Upper Paraná)	Central Upper Paraná contribution	Southern Upper Paraná contribution	Puerto Bermejo (Paraguay)
Jun 1983 (Autumn-N(+))	38.3	8.5 (5.4)	18.1 (13.3)	6.1	5.6
Jun 1992 (Autumn-N(+)	26.8	0.5 (2.5)	10.5 (13.3)	11.3	4.4
Dec 1982 (Spring/Summer-N(0))	26.1	4.4 (2.3)	9.4 (9.5)	7.6	4.6
Mar 1983 (Autumn-N(+))	24.2	8.4 (13.2)	8.8 (3.6)	3.8	3.4
Jun 1905 (Autumn-N(+))	24.2	N/A (N/A)	N/A (N/A)	N/A	N/A
May 1998 (Autumn-N(+))	23.0	0.4 (−1.0)	9.4 (16.3)	8.6	4.6[a]
Oct 1998 (Spring-neutral)	21.0	0.8 (−0.4)	15.2 (12.2)	1.0	4.1[a]
Oct 1983 (Spring-neutral)	20.5	5.9 (5.4)	6.4 (7.0)	6.0	2.2
Jul 1982 (Winter-N(0))	18.8	2.9 (3.7)	9.2 (2.9)	3.6	3.1
Feb 1997 (Summer-neutral)	17.7	0.9 (7.4)	12.8 (−2.0)	2.2	1.8
Sep 1989 (Spring-neutral)	16.7	1.0 (1.1)	8.5 (4.5)	3.8	3.4
Sep 1990 (Spring-neutral)	16.4	0.9 (0.7)	7.9 (5.2)	5.7	1.9
Jan 1912 (Summer-N(+))	15.9	N/A (N/A)	N/A (N/A)	N/A	N/A
Nov 1997 (Spring-N(0))	15.6	1.1 (0.3)	9.8 (9.2)	1.6	3.1
Jan 1966 (Summer-N(+))	15.4	3.3 (2.4)	2.6 (3.8)	6.5	3.0
Sep 1957 (Spring-N(0))	15.0	1.3 (0.9)	10.3 (8.4)	1.3	2.0

[a] Discharge data for 1995–98 were estimated considering river level data

Regulated discharges at Itaipú were utilized in this latter case because dams upstream from Itaipú regulate Corrientes discharges.

An accurate quantitative balance between the monthly discharges at Corrientes and upstream contributions shown in Table 2 cannot be expected since the discharge propagation cannot be correctly captured with one-month time resolution. In addition, the lag time between rainfall in the different sub-basins and the discharge response at the gauging stations at their outlet ranges from less than a month to one or more months (Camilloni and Barros 2000). Therefore, Table 2 allows to assess only the bulk magnitude from the sub-basin contributions to every major discharge event in Corrientes.

The largest contributions to the major discharge anomalies at Corrientes came from the central and southern Upper Paraná basins, especially from the first one. In general, these contributions constituted about two thirds or more of the discharge anomaly at Corrientes. Though always positive, discharge anomalies at Puerto Bermejo were considerably smaller than those of the Upper Paraná. Thus, the contribution from the Paraguay River to the major discharge anomalies at Corrientes adds to the contribution from the Upper Paraná, although in a relatively low proportion. The only cases with important contributions from the northern Upper Paraná occurred during the extraordinary El Niño 1982/1983 or a few months after its end. The small contribution from the northern Upper Paraná to the major discharges at Corrientes is peculiar, considering that this basin contributes with almost 40% of the annual mean discharge at Corrientes, and with little less than 50% of the Upper Paraná discharge.

Since with few exceptions, the major discharge events in Corrientes originate in the central and southern Upper Paraná basin, and especially in the first one, Table 3 presents the major anomaly contributions corresponding to this part of the basin [Itaipú + Salto Caxias − Jupiá] for the period 1931–1998. The table includes a classification of these events according to the season and the phase of the ENSO. The 18 events listed are those whose anomalies were higher than three times the standard deviation for the respective month. As in the case of the Corrientes discharges, the largest anomaly was registered in June 1983, but the rest of the events are not equally ranked as in the Corrientes case (Tables 2 and 3). However, there is a good correspondence between the highest discharge anomalies at Corrientes and those shown in Table 3.

Table 3
Maximum discharge contribution anomalies of the central Upper Paraná and the corresponding discharge anomalies at Jupiá and discharge contribution anomalies at Itaipú + Salto Caixas. Values in 10^3 m^3/s

Discharge peak date	Central Upper Paraná contribution	Jupiá	Itaipú + Salto Caxias
Jun 1983 (Autumn N(+))	18.1	8.5	26.6
Apr 1998 (Autumn N(+))	16.3	−1.0	15.3
Oct 1998 (Spring-neutral)	15.2	0.8	16.0
May 1992 (Autumn N(+))	13.3	2.5	15.8
Feb 1997 (Summer-neutral)	12.8	0.9	13.7
Jan 1995 (Summer-N)	11.5	−1.3	10.1
Oct 1935 (Spring- neutral)	11.2	1.4	12.6
Jan 1990 (Summer-neutral)	10.8	3.9	14.7
Sep 1957 (Spring-N (0))	10.3	1.3	11.7
May 1987 (Autumn N(+))	10.2	1.4	11.6
Nov 1997 (Spring-N(0))	9.8	1.1	10.9
Oct 1972 (Spring-N(0))	9.6	2.6	12.2
Nov 1982 (Spring-N(0))	9.5	2.3	11.8
Jul 1982 (Winter-N(0))	9.2	2.9	12.1
Mar 1983 (Autumn N(+))	8.8	8.4	17.1
Sep 1989 (Spring- neutral)	8.5	1.0	9.5
Sep 1990 (Spring- neutral)	7.9	0.9	8.8
Oct 1993 (Spring-N(0))	7.8	0.9	8.8

Contributions from the northern Upper Paraná to the major discharge anomalies in the central Upper Paraná are generally small—less than 25%—or even negative, except for a few cases during 1982 and 1983 (Table 3). Actually, the correlation between the contributions of monthly discharge anomalies from the northern and central Upper Paraná is only 0.25, which, though significant at the 95% level, indicates a weak relation between the precipitation variability over these two neighboring basins.

4. Climatic forcing of the major discharge anomalies

4.1. The annual cycle

The rainfall regime in the Upper Paraná basin changes from a pronounced annual cycle in the north to a less defined cycle over the Iguazú, southern Upper Paraná and Lower Paraguay basins (Camilloni and Barros 2000; Grimm et al. 2000). Over these regions, the impact of the South Atlantic Convergence Zone (SACZ) in summer is smaller than it is in the northern Paraná basin, and there is an important frequency of cyclogenesis during winter and spring (Gan and Rao 1991; Rao et al., 1996). In the Pantanal, rainfall presents a very pronounced annual cycle with a summer maximum. However, due to the extreme flatness of this region and the small runoff associated thereto, the maximum in the streamflow at Puerto Bermejo occurs with a lag of 5–8 months (Camilloni and Barros 2000). Because of these features, the river discharge at Corrientes has an attenuated mean annual cycle as compared with upstream discharges, but even so, during the 1931–1980 period, the mean discharge ranged from 12,000 m^3/s during August and September to around 21,000 m^3/s during February and March.

In spite of this well-marked annual cycle in the streamflow, the frequency of occurrence of major discharge anomalies at Corrientes was higher in autumn and spring (Table 2). This is a consequence of the seasonal variation of the precipitation response to El Niño in the Paraná basin (Grimm et al., 2000) and the link between most of these anomalies and El Niño. This was also observed in the central Upper Paraná, where only three of the 18 major contributions to discharge anomalies correspond to the December–February period (Table 3).

4.2. ENSO relationship

There is a clear relationship between ENSO phases and the major discharge anomalies in the Paraná River. In Corrientes, 11 out of 16 occurred during El Niño events (Table 2) and none of them occurred during La Niña phase. In the case of the major contributions from the central Upper Paraná, the proportion during El Niño phase was about the same, namely, two thirds (Table 3). In the northern Upper Paraná, this proportion was lower, as only 6 of the 13 major discharge anomalies occurred during El Niño phase and, as in the other two sub basins, there were no major discharge anomalies during La Niña phase.

The hydrological response to ENSO is consistent with the precipitation behavior, as the Upper Paraná basin is part of a region that has a strong precipitation signal from ENSO events (Kousky et al., 1984; Ropelewski and Halpert 1987,1996; Kiladis and Diaz, 1989). Nevertheless, the monthly and seasonal correlation between the SOI and the Upper Paraná discharge is relatively weak (Aceituno 1988). However, the link with ENSO is more explicit in the major discharges.

4.2.1. El Niño austral autumn

The top discharges of the Paraná River at Corrientes occurred during the austral autumn (March–June) of the year following the onset of El Niño event (autumn (+)). In five of the top-six major discharge anomalies that were simultaneous with the El Niño events of 1904–1905, 1982–1983, 1991–1992 and 1997–1998, El Niño SST anomaly in El Niño 3 region (greater than 0.5 °C) continued until May. In the other three El Niño events of the twentieth century in which El Niño SST anomalies continued until autumn (+) in El Niño 3 region, there were also important positive discharge anomalies at Corrientes, which occurred in March 1926 with 10,500 m^3/s; in May 1930, with 11,600 m^3/s; and in June 1987, with 10,900 m^3/s. Summarizing, during the twentieth century whenever El Niño 3 SST anomalies remained greater than 0.5 °C until the autumn (+) there were always important positive discharge anomalies at the Upper Paraná outlet. Actually, there is a quantitative relationship during autumn (+) between El Niño 3 SST and Corrientes discharge, as they have a significant (95% level) Spearman rank correlation (0.69) (Camilloni and Barros 2000).

The winter anomalous circulation of ENSO events over the western Southern Hemisphere was attributed to stationary Rossby wave propagation forced by the anomalous equatorial warming in the Central Pacific (Karoly 1989). An analogous wave propagation was described by Barros and Silvestri (2002) for the spring, and it could possibly be similar in autumn (+). During this season, the anomalous circulation increases the advection of cyclonic vorticity in the upper troposphere and the advection of warm and humid air at low levels, enhancing the precipitation over the central and southern Upper Paraná (Grimm et al. 2000).

As a result of these conditions, precipitation during autumn (+) season is important over the central and southern Upper Paraná and lower Paraguay basins. Fig. 2 presents the composite of rainfall anomalies for the March–May quarter corresponding to years when positive SST anomalies, over 0.5 °C, persisted in El Niño 3 region until May. According to this figure, there is little chance that this teleconnection might influence the Upper Paraná discharges. In fact, none of the major discharges at Jupiá took place in autumn (+).

4.2.2. El Niño austral spring

Five of the peaks that rank among the major streamflow contributions from the central Upper Paraná occurred during El Niño phase in spring (Table 3). This is in agreement with the general behavior of this streamflow contribution during the spring of the years of El Niño onset (spring (0)). In fact, these contributions presented small negative anomalies only in two out of 18 El Niño events that occurred during the 1931–1998 period, and in 10 cases their positive anomalies were considerable, ranging from 2,500 to 10,300 m^3/s.

As in the case of autumn (+), the largest anomalies in the composite rainfall for the spring (0) occurred in the central Upper Paraná basin, but with the maximum centered 300 km to the south with respect to the autumn (+) (Fig. 3). This anomaly field is consistent with the increase of the cyclonic vorticity advection in the upper troposphere (Barros and Silvestri 2002) and with the enhancement of the subtropical jet over South America (Grimm et al. 1998) during the spring (0). At this time of the year, baroclinicity over subtropical South America is important, and its enhancement during El Niño years favors the already frequent cyclogenesis and the development of mesoscale systems (Gan and Rao 1991; Velasco and Fritsh 1987).

4.3. Other climatic forcings

One third of the major discharge anomalies took place during the austral spring (September–November) or during the austral summer (December–February) of neutral periods and therefore, they were not forced by ENSO events. For their study, we will focus on the central Upper Paraná, where the neutral cases rank higher among the major discharge contributions than in the case of Corrientes (Table 3).

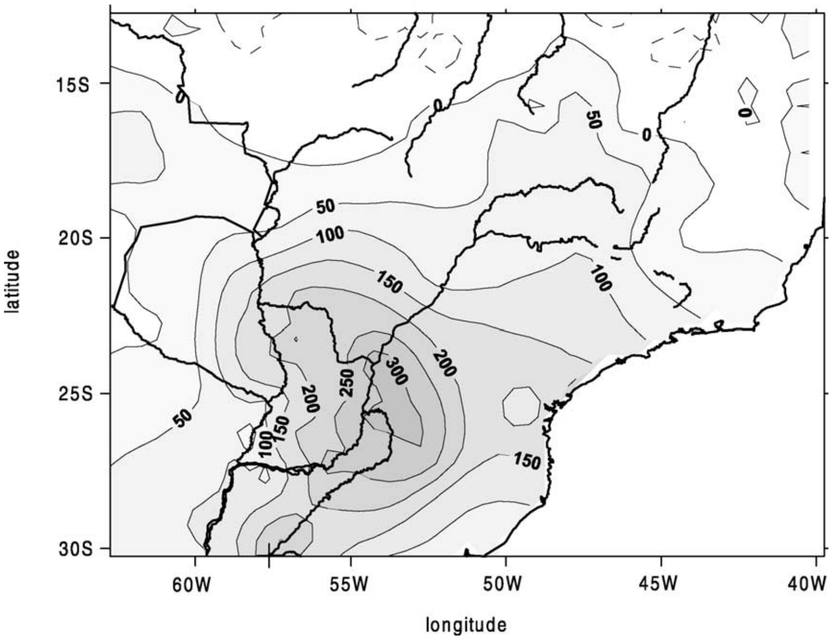

Fig. 2. Composite of rainfall anomalies for March (+) to May (+) of El Niño events that persisted until May in El Niño 3 region.

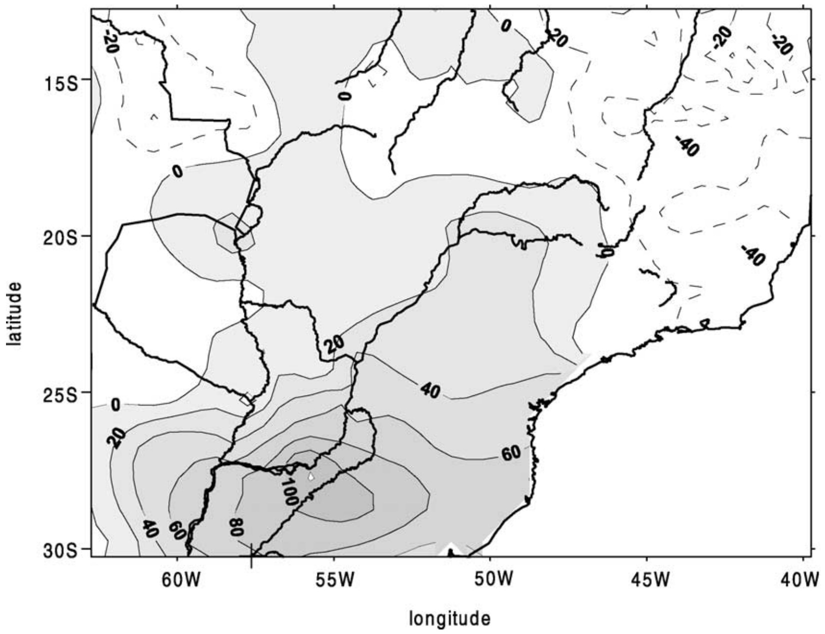

Fig. 3. As in Fig. 2, but for September to November of El Niño (0) years.

4.3.1. Neutral austral summer

The discharge contribution of the central Upper Paraná is significantly correlated at a 90% level with January–February SST over most of the subtropical South Atlantic (Fig. 4). This is particularly true west of 20°W, a region where SST is related to low-level circulation and precipitation over subtropical South America during midsummer (Doyle and Barros 2002). Another area of significant positive correlation is that of El Niño 1 + 2. However, there is no significant correlation with SST in the rest of El Niño regions, what is consistent with the lack of ENSO signal during midsummer. Actually, while precipitation has a strong ENSO signal in eastern subtropical South America during spring (0) and autumn (+), this signal vanishes during January–February (Grimm et al., 2000).

In view of the lack of El Niño signal in the midsummer precipitation in subtropical South America, other climate forcing could have caused the peak discharge of January 1995 (El Niño month). Therefore, this case is discussed together with the two neutral cases. Actually, SST anomalies in the three summers

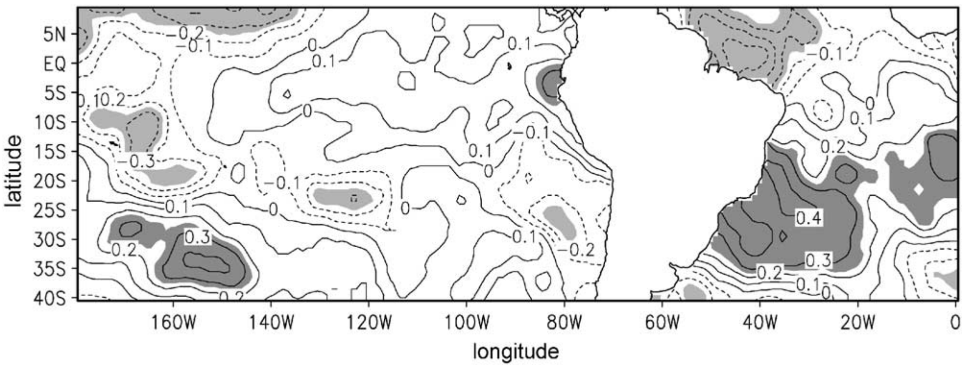

Fig. 4. January–February field of the linear correlation between the central Upper Paraná discharge and SST. Significant correlation coefficients at the 90% level are shaded.

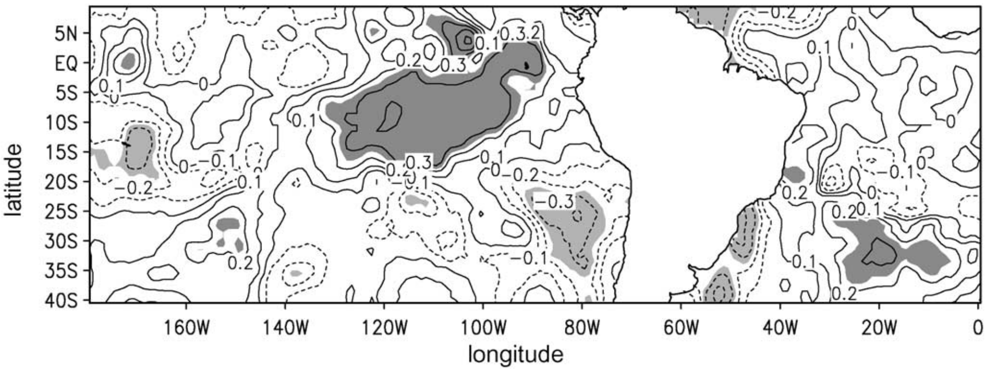

Fig. 5. As in Fig. 4, but for September-October of neutral years.

with major discharge contributions in the central Upper Paraná share common features. They have positive anomalies along the Pacific coast of South America from the Equator to 30°S, as well as in the subtropical Atlantic west of 20°W. These features are consistent with the correlation pattern shown in Fig. 4.

4.3.2. Neutral austral spring

When only neutral springs are considered, the discharge contribution from the central Upper Paraná is negatively and significantly correlated at a 90% level with September–October SSTs in both oceans near the coasts of South America, south of 20°S (Fig. 5). Over the eastern tropical Pacific, positive significant correlations predominate to the south of the Equator.

The SST anomalies corresponding to the four neutral spring cases of the major discharge contribution in the central Upper Paraná are shown in Fig. 6. October 1935 and September 1990 present cold anomalies off the coast of South America in both oceans, in accordance with the correlation pattern (Fig 6a and c). In the case of September 1989, the pattern in these regions is similar, although the anomalies are

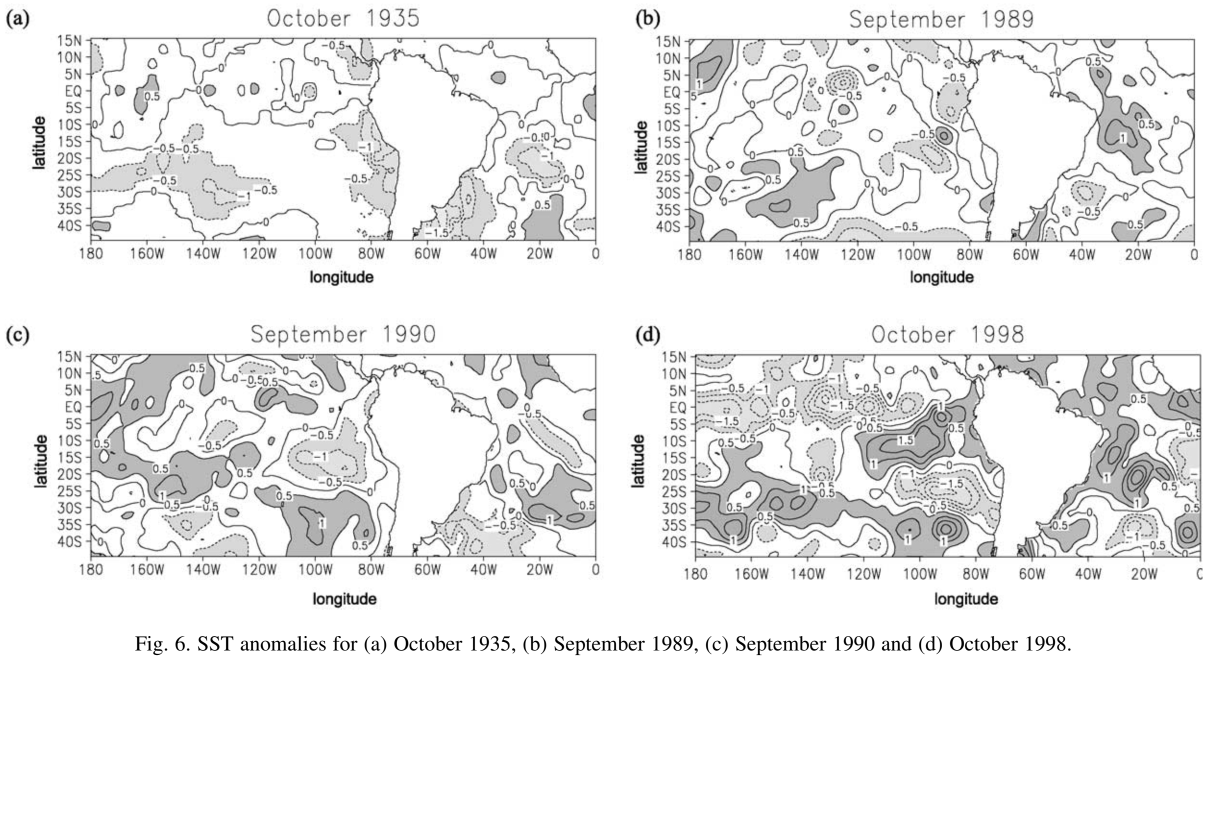

Fig. 6. SST anomalies for (a) October 1935, (b) September 1989, (c) September 1990 and (d) October 1998.

smaller (Fig 6b). Thus, these features, which according to the correlation pattern (Fig. 5) favor positive discharge anomalies, were observed during the months of the neutral spring cases of major anomalies in the central Upper Paraná contribution. The anomaly pattern over the eastern tropical and subtropical Pacific of October 1998 (Fig. 6d) was consistent with the correlation pattern that indicates that warm anomalies in the tropical eastern Pacific south of the equator are predominantly associated with greater than normal precipitation over the Upper Paraná basin.

5. The extraordinary 1982–1983 event

The impact of the strong El Niño 1982–1983 event in the Paraná streamflow was the greatest recorded. The river anomaly discharge in Corrientes exceeded 10,000 m^3/s from July 1982 to December 1983 (Camilloni and Barros 2000). In that period occurred five out of the 16 major discharge anomalies, i.e. in July and December 1982 and in March, June and October 1983 (Table 2). In June 1983 was registered the largest monthly discharge of the record started in 1904. The spatial extension of this impact was also exceptional, reaching the northern Upper Paraná, where three out of the 13 major discharges occurred during 1982–1983 including the top one registered in February 1983.

The peaks of March and June 1983 occurred during the autumn (+) of El Niño phase. During June 1983, the magnitude of the SST positive anomaly at El Niño 3 region was the highest of the entire record, and it was considerably higher than the average for El Niño events (Fig. 7). Therefore, according to the positive Spearman rank correlation mentioned earlier, this peak should be expected to be the highest among autumn (+) discharges at Corrientes (Table 2).

The peak of December 1982 originated in November 1982 in the upper Middle Paraná basin, but it received contributions from the other basins, including the central Upper Paraná basin. This case fits into the category of the spring (0) events that were associated with large positive discharge anomalies.

Other factors must have influenced the extraordinary precipitation during the austral winter of 1982, because in other El Niño cases with greater SST anomalies during the winter(0) the discharge response was smaller. Considering only the months when El Niño had already started, the rainfall anomalies during winter (0) were considerably large and positive over the central Upper Paraná basin (Fig. 8). This feature was also observed during the 1982 winter as can be inferred from Table 2. On the other hand, half of El Niño cases that took place during the 1951–1998 period had a SST positive anomaly in El Niño 3 region during the austral winter (0) that was equal to or greater than that observed in the 1982 event. For instance, in the case of the 1997 event, the positive

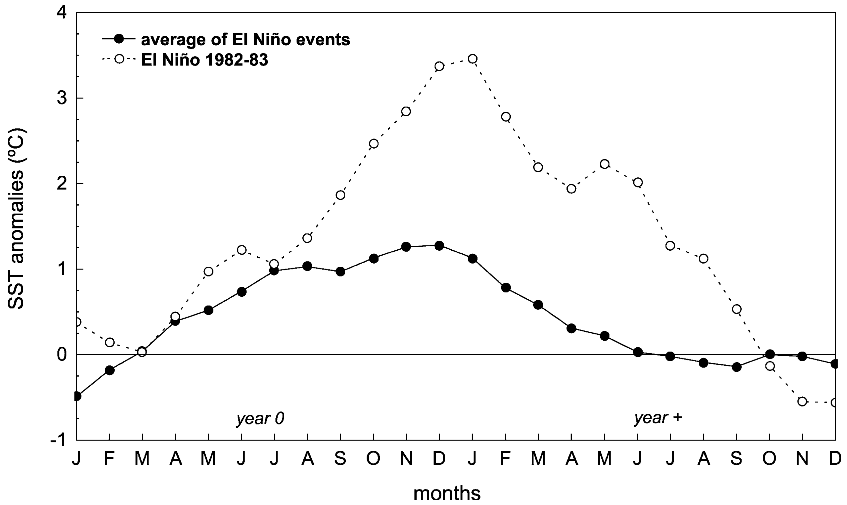

Fig. 7. SST anomalies in El Niño 3 region for the 1982–83 event and for the average of the twentieth century El Niño events.

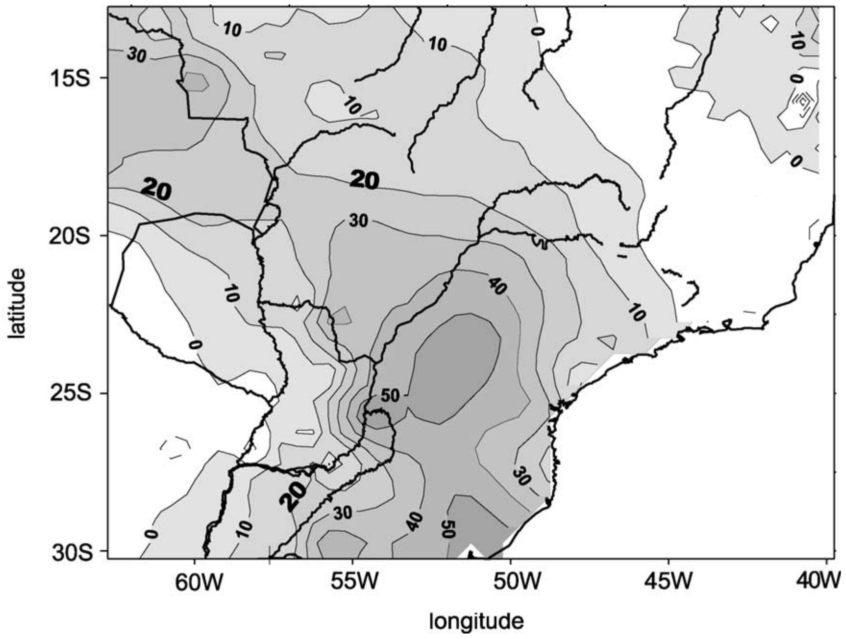

Fig. 8. As Fig. 2, but for June to August of El Niño (0) years.

anomaly in the discharge contribution from the central Upper Paraná was only of 6,300 m^3/s in July, contrasting with 9,200 m^3/s in 1982, although the respective SST at El Niño 3 region was almost 2 °C higher than in 1982.

In the case of the October 1983 peak, the anomalous SST at El Niño 1 + 2 region was still extremely high (1.5 °C) after the end of the El Niño episode (Fig. 9). For neutral springs, the correlation between the central Upper Paraná discharge contribution and SST at El Niño 1 + 2 region is significant and positive (Fig. 5). However, in October 1983, the contribution to the major discharge at Corrientes came also from the northern and the southern Upper Paraná basin indicating that, as in winter (0), other climatic factors could

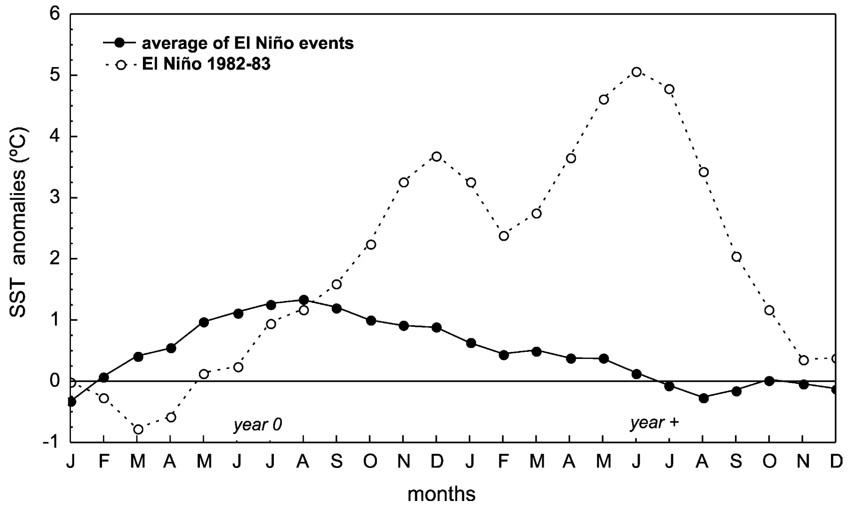

Fig. 9. As in Fig. 7, but for SST anomalies in El Niño 1 + 2 region.

be responsible for the extreme hydrological response of the Paraná River.

Although the conjunction of different factors could have contributed to the anomalous precipitation in the Paraná basin during the 1982–1983 period, the exceptional magnitude of these anomalies, and particularly their spatial extension and persistence before, during, and after El Niño event could need an additional and more comprehensive explanation.

6. Conclusions

Although the contribution from the central and southern Upper Paraná is only about 40% of the Corrientes mean discharge, the major discharges at Corrientes usually originated in these basins, especially in the central Upper Paraná. The contribution from the Paraguay River enhances the Upper Paraná major discharges, but in a relatively small proportion. On the other hand, the anomaly contribution from the northern Upper Paraná to the major discharge anomalies in Corrientes is, not only generally small, but also negative in some cases.

There is a clear relationship between the phases of ENSO and the major discharge anomalies in the Upper Paraná. About two thirds of the major discharge anomalies in Corrientes and of the major anomalous contributions from the central Upper Paraná occurred during El Niño events. In addition, none of these major anomalies occurred during La Niña phase. This contrasts with the weak monthly or seasonal correlation between the SOI and discharges at Corrientes, indicating that the major discharge anomalies were more related to El Niño phase than the rest of the discharge anomalies.

The major discharge anomalies in Corrientes and major discharge contributions from the central Upper Paraná that were related to El Niño occurred either in spring (0) or in autumn (+), accompanying the seasonal variation of El Niño precipitation signal in eastern subtropical South America. During the twentieth century, the top discharges of the Paraná River at Corrientes occurred in the autumn (+). In all of these events, SST anomalies in El Niño 3 region persisted until May (+) and also, whenever El Niño 3 SST anomalies continued until the autumn (+), there was an important positive discharge anomaly in the Upper Paraná.

The remaining third of the major discharge contributions from the Upper Paraná took place during the austral spring or the austral summer of neutral periods. During the summer cases, there were positive anomalies along the Pacific coast of South America from the Equator to 30°S, as well as predominant positive anomalies in the subtropical Atlantic west of 20°W. During neutral springs, the discharge contributions from the upper part of the Upper Paraná have significant negative correlation with the September–October SSTs south of 20°S in the proximity of both South American coasts, as well as significant positive correlation over the eastern tropical Pacific. The SST patterns for the neutral spring months with major discharge contributions from the central Upper Paraná were consistent with this correlation pattern, both in the eastern Pacific and near the South American continent, south of 20°S. However, as in the case of summer, there is no indication that these SST patterns were always accompanied by large anomalies in the discharge contribution from the central Upper Paraná. Thus, other atmospheric features not modulated by SST may have influence over the precipitation associated with some of the major discharge anomalies.

The extraordinary El Niño 1982–1983 event was accompanied by the highest monthly discharge registered in Corrientes and by a persistent anomalous high streamflow that went on from July 1982 to December 1983. Although the combination of different factors could have contributed to this long persistence during a year and a half, the exceptional magnitude of these anomalies and their spatial extension require a better understanding.

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