The Major Discharge Events in the Paraguay River: Magnitudes, Source Regions, and Climate Forcings

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ABSTRACT

The greatest discharges of the Paraguay River were studied using monthly series of Ladario, Brazil, at the outlet of the vast wetland of the Pantanal, and Asunción, Paraguay, at the middle Paraguay River outlet. Most of the major discharges at Asunción peaked between May and July, in phase with the annual maximum of the river discharges. They originated in the upper and middle Paraguay basins and were independent of the Pantanal output because their climate forcings were different from those of the Pantanal. In fact, most of the major discharge contributions from the upper and middle Paraguay basins occurred during El Niño (EN) periods, while at the Pantanal outlet they happened in neutral periods. The top discharge occurred during the autumn following the EN onset year. The composite of these cases has a tropospheric circulation that enhances the subtropical jet and the cyclonic vorticity advection over the Alto Paraná and the upper and middle Paraguay basins, favoring large positive anomalies in the precipitation field. Not all the major discharges were related to EN. Particularly, the major discharges that peaked in winter shared common features, despite their occurrence during EN, La Niña, or the neutral phases. Their April to August fields had an almost barotropic pattern at high latitudes with a deep cyclonic anomaly between 120° and 160°W and an anticyclonic anomaly over the southern tip of South America. This pattern is consistent with a northward shift of the synoptic perturbation tracks, which favors fields of positive precipitation anomalies over the Paraguay basin.

1. Introduction

The Paraguay River is the most important tributary of the Paraná River and one of the main constituents of La Plata basin, the fifth largest basin in the world. The area of the Paraguay River basin exceeds 1 million km^2 and includes the Pantanal, a huge and flat wetland of 140 000 km^2 (Fig. 1). The Pantanal wetland is a great complex of inundated floodplains. This region, one of the largest wetlands of the world, is widely recognized for its ecological importance and its huge wildlife resources, representing a priority for international conservation endeavors. A navigation project of four countries, known as the Paraná–Paraguay Waterway, would deepen and modify the Paraguay River channel to facilitate navigation through the Pantanal. This channel alteration constitutes a potential hazard for the Pantanal environment, as the Paraguay River is the major draining course of the inundated floodplains (Hamilton 1999). The inability of the Paraguay River to carry the summer runoff causes the seasonal inundation of the Pantanal, which acts as a buffer delaying and distributing in time the river discharge. The channel modification may reduce this buffer effect, affecting the floodplain ecosystems. Another concern with the waterway is its effect on the peak floods downstream of the Pantanal.

Downstream of the Paraguay River outlet from the Pantanal, large discharges inundate the floodplain to a width of 5–10 km, mostly along the right bank of the river. Before instrumental records—that is, before 1904—the major floods, as estimated from their catastrophic impacts described in historical chronicals, were in the years 1612, 1748, 1812, 1858, and 1878 (Bunning and Pettras 1979). Of similar effects were those in the instrumental record period starting in 1904, namely, in

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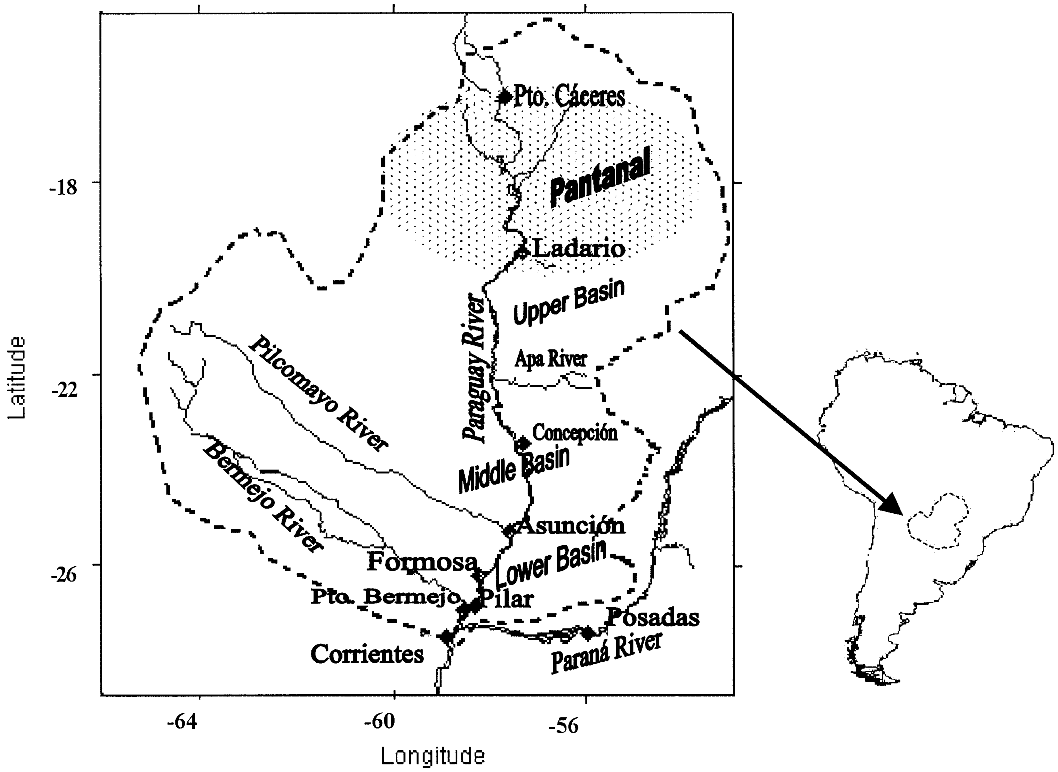

FIG. 1. The Paraguay River basin.

1905, 1982–83, 1992, and 1997–98. These and another less critical floods cause severe economic losses affecting thousands of settlers. For instance, during the last two huge floods of 1982–83 and 1997–98, the National Emergency Committee of Paraguay (1998) estimated that the total number of persons evacuated was around 70 000 and 105 000, respectively.

Although there were long records of water levels at a few locations, the lack of discharge measurements at the outlet of the Pantanal or in upper Paraguay River hampered the progress of technical work dealing with the causes and features of the major floods, and fostered what, according to this paper's results, are erroneous views. In particular, there is a widespread belief that floods downstream of the Pantanal decisively depend on the contribution from this wetland (e.g., Bertoni et al. 2003). It was not until 1996 that the Ladario, Brazil, rating curve was constructed. In view of this deficit of knowledge, and because of the social and economic impact of these floods, the objective of this paper is to characterize the largest discharges of the Paraguay River in terms of their magnitude, source region, and climate forcing. Special attention is paid to the contribution of the Pantanal to the largest Paraguay River discharges using the rating curve based on measurements taken in 1996.

The paper has five sections. Section 2 deals with the necessary background for the core subjects treated in sections 3 and 4; it describes the mean Paraguay River hydrology and datasets. Section 3 characterizes the greatest discharges, their seasonal behavior, and their source regions. Section 4 discusses the climate forcing of these events, whose impacts are common to a broader area in South America. To conclude, section 5 summarizes the main results.

2. Mean hydrology and data

With the exception of the source areas of two of the Paraguay River tributaries, the Pilcomayo and Bermejo Rivers, which descend from the Bolivian Plateau, the Paraguay basin extends over a vast plain of a million square kilometers. Its altitude ranges from 125 m above sea level at the Pantanal entrance to 48 m at its confluence with the Paraná River. It has a long course of 2500 km with a large number of meanders. Because of this size and its extremely small gradient, its highest discharges evolve gradually, persisting several months. Thus, monthly resolution permits a description of the general features of these events.

From the Pantanal outlet at Ladario, to the confluence with the Apa River, the Paraguay River is known as upper Paraguay, and it serves as border between Brazil and Paraguay. Downstream of this point, the river flows inside Paraguay to its confluence with the Pilcomayo River at Asunción, Paraguay. This section receives the name of the middle Paraguay. From Asunción, to its outlet in the Paraná River, the river is known as the

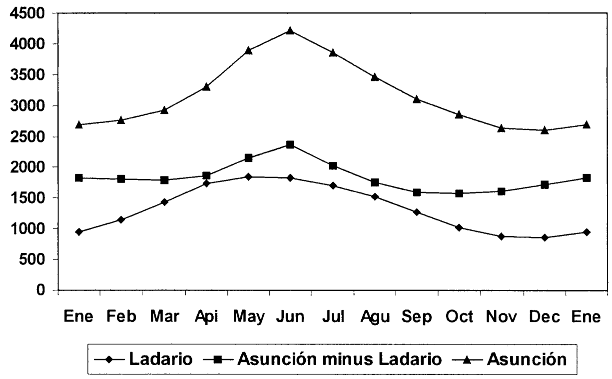

FIG. 2. Mean monthly discharges 1950–98 in $m^3 s^{-1}$.

lower Paraguay. The annual mean discharge of the Paraguay River is approximately 4200 $m^3 s^{-1}$, which results from contributions from the Pantanal (30%), the upper and middle Paraguay basins (45%), and the lower Paraguay basin (25%).

Precipitation in the Pantanal has a monsoon regime. Most of the rainfall occurs between October and March, gradually filling this huge depression (Lacerda de Almeida and Barros 1998; Hamilton 1999; Collischonn et al. 2001; Bertoni et al. 2003). The water accumulates in this big natural reservoir and slowly runs off into the Paraguay River. This regulatory effect delays the annual peak for about 3 to 4 months. Upstream of the Pantanal at Puerto Cáceres, Brazil, the annual peak usually occurs in February or March in phase with precipitation, while downstream at Ladario, the peak occurs between April and June. This regulation also dampens the amplitude of the annual cycle of the streamflow with respect to that of the precipitation cycle (Camilloni and Barros 2000). Even so, there is a factor of 2 between the maximum and minimum monthly discharge.

In the rest of the Paraguay River basin, the precipitation also has a monsoon regime, with summer precipitation 3 times greater than winter precipitation. However, the contribution of the upper and middle basins to the Paraguay River discharge, measured as the difference between Asunción and Ladario discharges, increases from February to June, when it reaches its maximum value (Fig. 2). This is because the maximum of the difference between rainfall and evapotranspiration is in the autumn months when, though precipitation is lower than in summer, it exceeds considerably the evapotranspiration. The annual cycle of the upper and middle basins' contribution to the Paraguay River discharge reinforces the annual cycle of the discharge flowing out of the Pantanal and thus the hydrogram of Asunción presents a maximum in June and a minimum in December, opposite in phase to the monsoon rainfall regime of the basin.

The Ladario and Asunción monthly discharge series are the key data for this study as they are indicative of the Paraguay River streamflow at the Pantanal and the middle basin outlets, respectively (Fig. 1). Asunción discharges (1904–98) were taken from the Hydraulic Laboratory of the National Administration of Navigation and Ports of Paraguay. Ladario discharges were calculated from the river levels (1904–98) with a rating curve based on measurements taken in 1996 for the study of the navigation system of the Paraguay and Paraná Rivers (Hidroservice–Louis Berger–EIH 1996). The river at Ladario is wide, and its extent is sometimes uncertain (Collischonn et al. 2001). This may contribute to some error in the calculated discharges, but they do not seem to compromise the conclusions of the study, which are independently corroborated by rainfall fields.

Downstream of Asunción, except for Puerto Bermejo, Argentina, close to the confluence with the Paraná River, there are not long records of discharges. The Puerto Bermejo series is available from the Argentine Water Resource Secretary (http://www.mecon.gov.ar/hidricos/mapashidricos/mapageneral.htm). During the major Paraguay River floods, Puerto Bermejo presented an apparently lower discharge than Asunción. This is because for large discharges, the river overflows its channel, and therefore its rating curve does not correctly calculate the real discharges. In addition, with large discharges in the Paraná River, there is a backwater effect in the Paraguay River reaching upstream as far as Formosa, Argentina, and again in these cases, the Paraguay River discharges are not well estimated from the rating curve of Puerto Bermejo. For these reasons, this downstream limit of this study was placed at Asunción.

The University of Delaware precipitation series (Willmott and Matsuura 2001), sea level pressure (SLP), geopotential, and streamfunction from National Centers for Environmental Prediction–National Center for Atmosphere Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996), all available from National Oceanic and Atmospheric Administration–Cooperative Institute for Research in Environmental Sciences (NOAA–CIRES) Climate Data Center, were used to explore possible climate teleconnections. Precipitation fields allowed verification that discharge anomalies were actually responding to climate events and were not the result of mistakes in the measurements or in the handling of the hydrological data.

Sea surface temperature (SST) was taken from the Global Sea Ice and SST dataset (GISST), version 2.3b, of the British Atmospheric Data Center. SST data before 1950 are not very reliable because of discontinuities in the observing systems, and in the case of the Southern Hemisphere because of the very sparse observations. On top of that, earlier than 1960 NCEP–NCAR reanalysis data are less reliable over South America since they were based only on surface observations. Because of these shortcomings, the climate forcing of only the large discharge events following 1960 was analyzed.

3. The major discharges

The mean monthly discharge of the Paraguay River at Asunción during the 1950–90 period was 3190 $m^3 s^{-1}$,

TABLE 1. The major discharge peaks ordered according to Asunción discharge (1904–98). Duration refers to the period with monthly discharges exceeding 6230 $m^3 s^{-1}$. Autumn (+) indicates the autumn of the year following the year of El Niño onset. Values in Ladario were taken a month before the monthly peak in Asunción.

Rank	Year	Month	ENSO phase	Duration	Discharge ($10^3 m^3 s^{-1}$) Asunción	Asunción−Ladario	Ladario
1	1905	Jun	EN [autumn (+)]	Mar–Sep	11.0	9.1	1.9
2	1983	Jun	EN [autumn (+)]	Mar–Aug	10.7	8.1	2.5
3	1992	Jun	EN [autumn (+)]	May–Jul	9.7	7.3	2.3
4	1988	Jul	LA	Jun–Aug	8.6	6.0	2.6
5	1982	Jul	EN	Jul–Oct	8.4	6.2	2.2
6	1919	Jun	EN [autumn (+)]	Jun	8.3	7.1	1.1
7	1931	Jun	LA	May–Jun	7.9	5.4	2.5
8	1979	Jun	Neutral	May–Aug	7.5	4.9	2.7
9	1998	May	EN [autumn (+)]	May	7.4	6.4	1.0
10	1913	May	EN	May–Jun	7.2	3.8	3.3
11	1983	Jan	EN	Dec–Jan	7.1	6.0	1.2
12	1912	Jan	EN	Dec–Jan	7.1	6.3	0.7
13	1985	Jun	LA	May–Aug	7.0	4.2	2.8
14	1980	Jul	Neutral	Jul	6.5	4.2	2.3
15	1997	Dec	EN	Dec	6.4	5.7	0.7
16	1965	Jun	EN	Jun	6.4	5.2	1.2

with a standard deviation of 1520 $m^3 s^{-1}$. Table 1 lists the monthly discharge peaks that exceeded the mean discharge plus two standard deviations, that is, 6230 $m^3 s^{-1}$. From the beginning of the record in 1904, there were 16 of these extreme discharges. Hereafter, these 16 discharges will be referred to as the major discharges.

The peaks of the major discharges at Asunción usually took place during June, in phase with the maximum of the river discharges, but sometimes they occurred in May or July (Table 1). There were, however, three exceptions with peaks in December or January, but none of them ranks among the top 10 major discharges. The major discharges persisted several months; in most cases, the exceptional level of 6230 $m^3 s^{-1}$ was exceeded in three successive months, and in the two top peaks in six and seven consecutive months.

The major discharges originated in the upper and middle Paraguay basins to the south of the Pantanal, as can be appreciated comparing the contributions of this section with discharges at Ladario (Table 2). Only in the 1913 event, the discharge from the Pantanal was almost equivalent to that of the upper and middle basins. This result refutes the widespread belief, prevalent in the local technical spheres, that the occurrence or not of great discharges in the Paraguay River are considerably dependent on the Pantanal water storage.

El Niño (EN), neutral, and La Niña (LN) months were identified following Trenberth (1997) for the 1950–96

TABLE 2. As in Table 1, except that cases are ranked according to the anomalies of the discharge differences between Asunción minus Ladario. Only cases with this anomaly exceeding 2400 $m^3 s^{-1}$, twice the standard deviation of the 1950–90 period, were included. Duration refers to the period with the anomaly persisting over this value. Ladario discharges were taken as in Table 1.

Rank	Year	Month	ENSO phase	Duration	Discharge anomalies ($10^3 m^3 s^{-1}$) Asunción−Ladario	Asunción	Ladario
1	1905	Jun	EN [autumn (+)]	Dec–Dec	6.7	6.8	0.1
2	1983	Jun	EN [autumn (+)]	Dec–Aug	5.8	6.5	0.7
3	1992	Jun	EN [autumn (+)]	May–Jun	5.1	5.5	0.4
4	1919	Jun	EN [autumn (+)]	Jun–Jul	4.8	4.1	−0.7
5	1912	Jan	EN	Dec–Jan	4.5	4.4	−0.1
6	1982	Aug	EN	Aug–Nov	4.4	4.9	0.5
7	1998	May	EN [autumn (+)]	Mar–May	4.2	3.5	−0.7
8	1988	Jul	LA	Jul–Sep	3.9	4.7	0.8
9	1931	Jun	LA	Jun	3.1	3.7	0.6
10	1979	Sep	Neutral	Jul–Sep	3.0	3.3	0.3
11	1995	Feb	EN	Feb	2.9	2.9	0
12	1908	Mar	LA	Mar	2.9	2.5	−0.3
13	1920	Dec	Neutral	Nov–Dec	2.9	3.4	0.5
14	1965	Jun	EN	Jun	2.9	2.2	−0.7
15	1956	May	LA	May	2.8	2.2	−0.7
16	1989	Oct	Neutral	Sep–Oct	2.5	3.1	0.6
17	1980	Aug	Neutral	Aug	2.4	2.7	0.3

period, the Climate Prediction Center for 1997–98, and Kiladis and Diaz (1989) and our own estimates from SST for the 1904–49 period. There is a marked relation between EN phase and the major discharges. The three top discharges occurred during EN phase in the autumn of the year following the onset of an EN event [denoted autumn (+)] and two-thirds of the major 16 discharges (11/16) during EN phase. This ratio could have occurred either because EN SSTs forced these major discharges in the Paraguay River by an atmospheric mechanism, or merely by chance because other climate forcings would be indeed responsible for these discharges. To explore the last possibility, we use the fact that the occurrence of a major discharge during EN phases or during the rest of the time are events of only two possible outcomes, whose distribution follows a Bernoulli distribution (Keeping 1962). Thus, the probability that a given ratio could have happened by chance is

$$\text{Pn}(x) = \{n!/[(n - x)!\, x!]\}\, p^{(x)} q^{(n-x)}. \qquad (1)$$

In this case, Pn (x) is the probability that the observed frequency (x) of major discharges occurred during EN phases, out of a total of n major discharges. The probability of EN month occurrence is p, and q is the probability of no EN months, hence $q = 1 - p$. The probability (P) of this ratio or a larger one is

$$P = \sum_{x}^{n} Pn(i) \qquad i = x, x + 1, \ldots, n - 1, n. \qquad (2)$$

Since in the 1904–98 period, the rate of months during EN phase was approximately 0.3, according to Eqs. (1) and (2), the probability that 11 or more of the major 16 monthly discharges occurred during a month of EN phase by chance is less than 0.5%.

Not all of the major discharges were related to El Niño. Indeed, almost a third of them occurred during the other phases of the El Niño–Southern Oscillation (ENSO), two during the neutral phase and three during LN. This implies that other climate forcings different from EN could also favor the occurrence of major discharges in the Paraguay River. Although the Paraguay River basin lies in southeastern South America, a region with a considerable rainfall correlation with ENSO indexes (Ropelewski and Halpert 1987), the influence of ENSO in the Paraguay River basin is less important than over the Paraná basin (Grimm et al. 2000). Thus, in many EN years, discharges were not very large, and therefore, it is not surprising that other climate processes, different from EN, could have forced some discharges that rank between the major 16 of the Paraguay River.

In order to discuss climate forcing, it is convenient to study the anomalies with respect to the mean monthly values. Because the major discharges originate in the upper and middle basins, the anomalies of the Asunción minus Ladario difference were calculated; Table 2 ranks the cases that exceeded two standard deviations. As in the case of Asunción discharges, hereinafter these extreme cases are referred to as the major anomalies. Although most of these major anomalies occurred during the May to July period, especially in the case of the top ones, there were others at almost every time of the year.

The relation with EN is similar to that of the Asunción discharges, being more evident in EN autumn (+) cases, as the four top anomalies and five out of the top seven occurred during these months of the EN phase. However, the rate of the major peak anomalies during EN months is lower (9/17), though again, the probability that this rate, or a greater one, took place by chance according to the Bernoulli distribution is still low, about 4%. Despite this clear signal, almost half of the major peak anomalies still bear no relation to the ENSO phase, as they occurred during LN and the neutral phases.

Despite being in the same river, the major discharges at Ladario were not associated with those at Asunción. Likewise, discharge anomalies at Ladario did not contribute substantially to the respective anomalies in Asunción discharges, and they were not correlated, either considerably or significantly, with the contribution from the upper and middle basins. This implies that the climate forcings in the Pantanal associated with the major discharges are different from those of the upper and middle basins.

There is no signal that the major discharges at the Pantanal outlet were caused by EN or LN events. On the contrary, out of their 14 highest discharges, 9 occurred during a neutral phase. The probability that 9 or more of the major 14 discharges occurred during the neutral phase by chance is less than 10%. This probability was calculated from a Bernoulli distribution as in the former cases with a frequency of neutral cases of 0.43. The lack of an ENSO signal on the major discharges of the Paraguay River at the Pantanal outlet is consistent with the fact that this region lies between 10° and 20°S, which is a transition region regarding the sign correlation between the ENSO indexes and rainfall. North of this region, LN phase is associated with enhanced precipitation while EN is related to lower-than-normal rainfall (Ropelewski and Halpert 1996; Souza et al. 2000), and the opposite relation holds to the south (Grimm et al. 2000).

Only one of the major discharges at Asunción was observed during the 40-yr period beginning in 1935 (Fig. 3a and Table 2). This event was in 1965, and it was not one of the top ones, ranking only sixteenth according to Asunción discharges. In addition, the mean annual discharges were below their mean value during most of these 40 yr, reflecting the fact that the maximum monthly peak of each year and the annual mean discharge are highly correlated (0.9). For Ladario, this correlation is 0.98. These high correlation coefficients indicate that the discharge waves are many months long, of the order of a year, and thus their monthly peaks tend

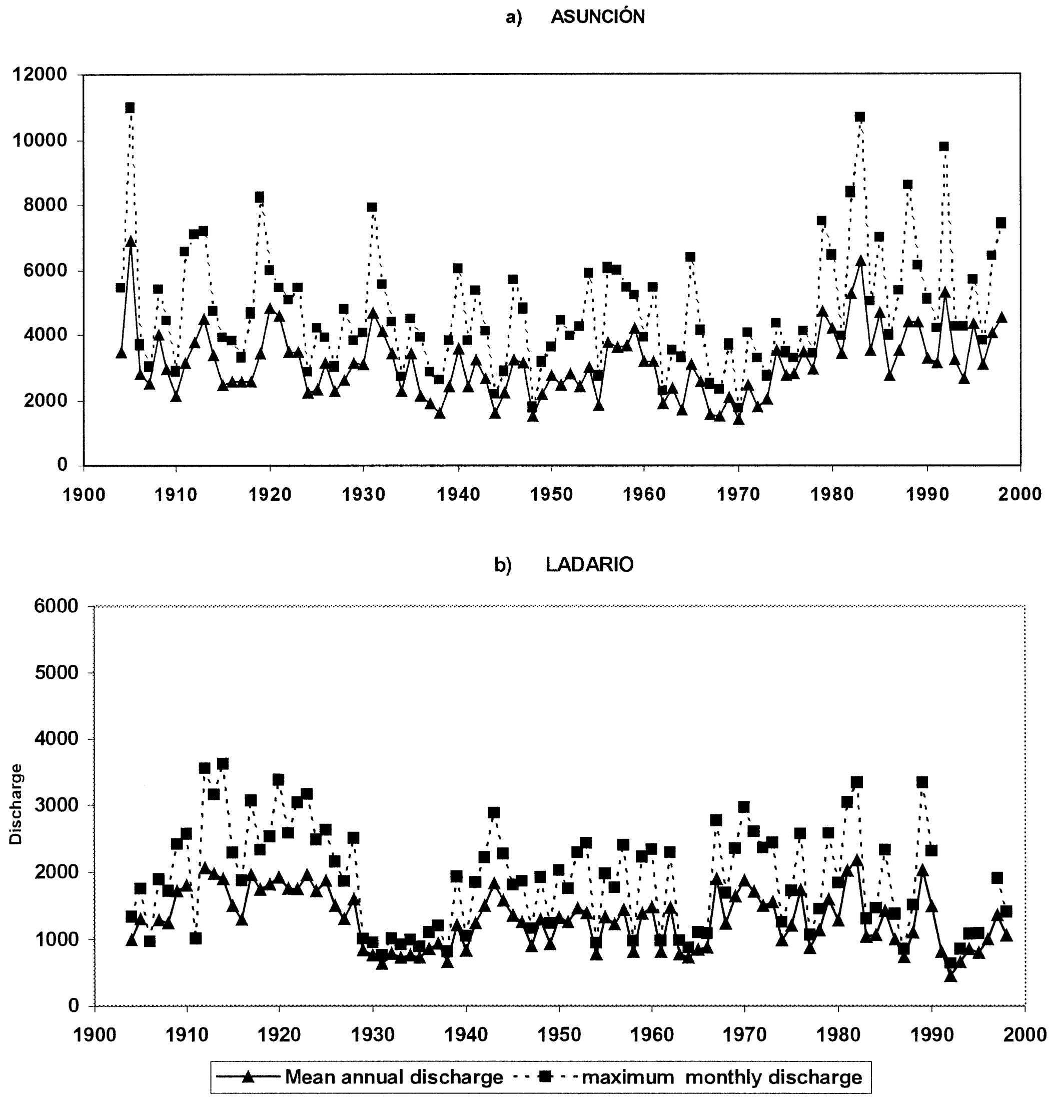

FIG. 3. Monthly peak value of the year and mean annual discharges for (a) Asunción and (b) Ladario.

to be approximately proportional to the mean annual discharge.

Figure 3 shows the series of the annual mean and the monthly peak of each year. Both Ladario and Asunción annual discharges had important interdecadal variability. The low-frequency variability of the Paraguay River has been described by Genta et al. (1998) and documented in detail by Collischonn et al. (2001). Here, we stress the fact that the interdecadal variability of the annual discharge at Asunción was not exactly in phase with that of Ladario, reflecting the incidence of the interdecadal variability of the upper and middle Paraguay contribution. The long 40-yr period of low annual discharges seems to be the result of climate forcings that had more effect in the upper and middle Paraguay basins than in the Pantanal.

4. Climate forcings

The most studied teleconnections between the climate of southeastern South American and remote forcings are the ENSO signals. Several studies (Ropelewski and Halpert 1987, 1996; Aceituno 1988; Kiladis and Diaz 1989; Pisciottano et al. 1994; Camilloni and Barros 2000; Grimm et al. 2000; Montecinos et al. 2000) support the existence of links between SST anomalies in the tropical Pacific with precipitation anomalies in subtropical South America. Grimm et al. (2000) showed that the most significant impacts of El Niño events on rainfall in this region start in spring of the onset year of the event, but the signal almost disappears during summer and comes back during the autumn and early winter of the year (+).

Consistent evidence of the link between the Paraná discharges, including the Paraguay contribution, and ENSO have been reported. For example, Aceituno (1988) found a weak negative correlation between discharges of the Paraná and the Southern Oscillation index during November–April. 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. El Niño was usually accompanied by the enhancement of the Paraná River flow, while LN has an opposite behavior (Berri et al. 2002). Robertson et al. (2001) analyzed the interannual to decadal predictability of the Paraná River extracting near-cycling components of the summer river streamflow. Their results show that the ENSO oscillatory component is associated with changes in the probability distribution of monthly flows and that the decadal modulation of ENSO is important, although the predictability due to ENSO at interannual lead times is small. Camilloni and Barros (2003) showed that about two-thirds of the major discharge anomalies in Corrientes occurred during EN events, while none was registered during LN phases.

Of the 17 major anomalies in the difference between Asunción and Ladario discharges, the most unambiguous signal is that of the five cases that occurred during EN autumn (+). Another case took place in the autumn of the onset year of EN [denoted autumn (0)] in 1965. As will be shown later, the five cases in which the peak anomaly was between July and October share a common climate pattern in spite of occurring during any of the three ENSO phases, as three of them occurred during the neutral phase, one during EN, and the other during LN. The summer cases also occurred during EN, LN, or the neutral phase of the ENSO, but since three out of the four cases took place before 1960, they are not analyzed here because of the reasons outlined in section two. Neither of the remaining two cases that took place during LN autumns before 1960 is discussed for the same reason.

a. El Niño autumn (+)

Under similar humid conditions, the subtropical latitude of the upper and middle Paraguay basins favors a smaller evapotranspiration during autumn than in summertime. Hence, the autumn positive precipitation anomalies are very efficient in their contribution to the Paraguay River discharge.

During the twentieth century, whenever El Niño SST anomalies in the central equatorial Pacific persisted until the autumn of the year (+), there was an important atmospheric teleconnection between SST in the central equatorial Pacific and southeastern South America, namely, the region between 15° and 35°S east of 60°W (Camilloni and Barros 2000). The composite of March–May precipitation anomalies of EN autumn (+) shows an important positive anomaly of more than 80 mm month^{-1} centered in the Alto Paraná basin that also affects the eastern part of the upper and middle Paraguay basin, confirming that the top discharges in the Paraguay River did not originate in the Pantanal (Fig. 4).

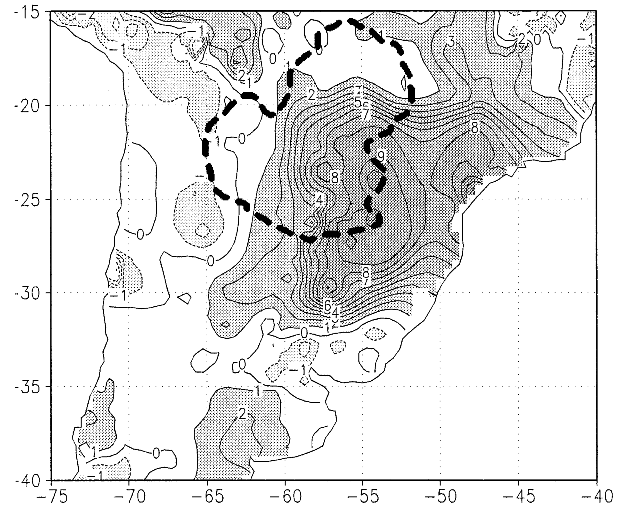

FIG. 4. Composite of the Mar–May period (years 1953, 1987, and 1992) corresponding to the EN cases that persisted until the autumn (+). Precipitation anomalies in cm month^{-1}. The dashed contour line shows the Paraguay River basin.

Consistent with this precipitation anomaly field, the top major discharges in the Paraná River also occurred during EN autumn (+) (Camilloni and Barros 2003). In this river, there was a close correspondence between the major discharges and the persistence of the EN phase until the autumn (+). In all EN cases that persisted until the autumn (+), there were large positive anomalies, more than 10 000 m^3 s^{-1}. On the other hand, this precipitation signal was more marginal in the Paraguay basin. Thus, in certain cases, when the core of the positive precipitation anomaly was shifted southward or eastward, anomalies were less conspicuous over the eastern part of the Paraguay basin. This occurred in 1926, 1930, and 1987 when discharges in the Paraguay River did not rank among the most important ones as they did in the Paraná River. On the other hand, all EN events between 1982 and 1998, namely, in 1982/83, 1986/87, 1991/92, and 1997/98 persisted until the autumn (+). These cases contributed to the positive trend in the monthly peaks shown in Fig. 3a.

The SST corresponding to the autumn (+) (not shown) presents the well-known pattern of EN, with warmer than usual temperatures at the eastern equatorial Pacific Ocean and large positive anomalies off the coast of South America. Consistent with the persistence of positive anomalies in the equatorial Pacific, there is an anticyclone anomaly circulation pair in the upper troposphere over the central and eastern Pacific straddling from the equator in each hemisphere (Fig. 5). Over southern South America, a strong cyclonic anomaly dominates the circulation field over this part of the continent. Its position with respect to the anticyclonic

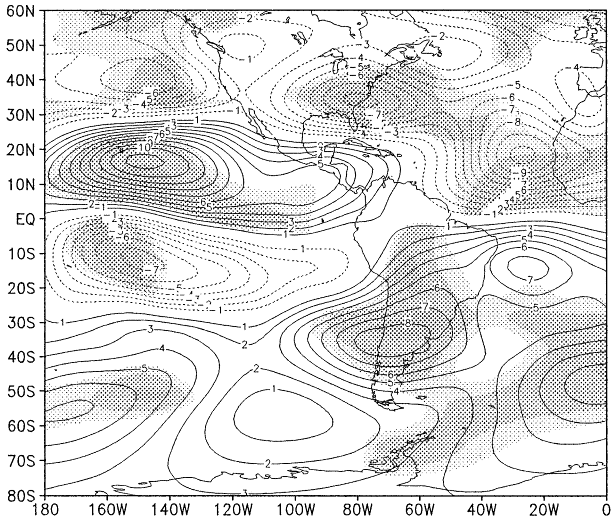

FIG. 5. As in Fig. 4, but for streamfunction anomalies at 200 hPa in 10^{-6} m^2 s^{-1}. Shaded areas show significance at levels 90% (light gray), 95% (medium gray), and 99% (dark gray).

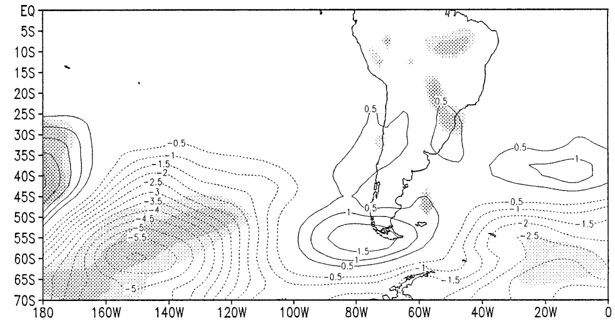

FIG. 6. Composite of anomalies for the Apr–Aug period of the years 1979, 1980, 1982, 1988, and 1989, with SLP in hPa, and shaded areas as in Fig. 5.

anomaly suggests the propagation of a stationary Rossby wave–like train induced by the equatorial source of EN, but shifted eastward of the so-called Pacific–South American pattern mode 1 (PSA-1) (Karoly 1989; Mo 2000). This anomaly circulation enhances the cyclonic vorticity advection over the upper and middle Paraguay and upper Paraná basins and the subtropical jet, which favors the development of cyclogenesis (Gan and Rao 1991) and mesoscale convective systems (Velasco and Fritsch 1987), the two important mechanisms that produce the largest rainfalls in southeastern South America. It can be concluded that during the autumn (+), the strong positive precipitation anomalies observed in southeastern South America are consistent with the circulation anomaly field associated with EN.

b. El Niño autumn (0)

During the autumn (0), EN has not yet been initiated or is in its early stage. The rainfall composition (March–June) of the cases when the EN already started (1953, 1957, 1965, 1972, 1982, 1991, and 1993) shows positive anomalies centered over the northeast of Argentina and south of Brazil that stretches over the upper and middle Paraguay basins and south of the Pantanal. Over these basins, the anomalies are much lower than in the composite of autumn (+), reaching only about 50 mm for the 3 months (not shown). This weak signal is consistent with the fact that there was a major anomaly in the contribution of the upper and middle Paraguay basins only in one case, in 1965.

The SST composition shows the typical anomalies of El Niño in the tropical and equatorial Pacific, though they are yet not very warm. In the upper troposphere, the anticyclonic circulation appears only in the Southern Hemisphere, westward of its position during the autumn (+). Because of that, the stationary wavelike train propagates more to the west, and there is only a weak cyclonic circulation anomaly over Paraguay, which is consistent with the weak positive anomalies of the precipitation field.

c. The winter cases

The major contribution anomalies of the upper and middle Paraguay of 1979, 1980, 1982, 1988, and 1989 share common features. One of them is that all peak later than the mean annual maximum, that is, in the period July to October. The second common feature is that the average SLP from April to August of each case shows a deep low anomaly at high latitudes between 120° and 160°W and a high anomaly centered in the southern tip of South America. Naturally, this pattern also appears in their composite (Fig. 6). These anomalies extend over the whole troposphere being almost barotropic, especially in the case of the anticyclonic circulation. These anomalies reflect frequent blocking conditions in the circulation (Renwick 1998). Because of this blocking effect, the frontal and cyclonic perturbations enter the continent more to the north than usual (Garreaud and Battisti 1999) and they have a trajectory farther west than in the typical conditions. Figure 7 shows the composition of precipitation anomalies reflecting these situations. There are not precipitation anomalies in western Argentina because of the lack of water vapor, which is characteristic of the winter in this region. Consistent with a probable northwestward displacement of the perturbation tracks, there is a strong negative precipitation anomaly in eastern Argentina, Uruguay, and south of Brazil (Fig. 7), while there are positive anomalies reaching more than 50 mm for the 5-month period over the eastern part of the upper and middle Paraguay basins and the Pantanal. The positive anomalies stretch in a band from Bolivia to the state of São Paulo, Brazil. Although these anomalies are considerably lower than in the autumn (+) case, they imply a precipitation exceeding considerably the normal evaporation, especially during July and August.

The described features of the composites shown in

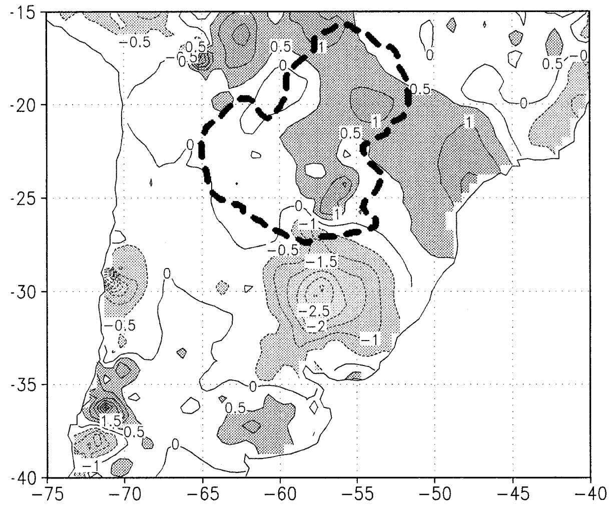

FIG. 7. As in Fig. 6, but for precipitation in cm month^{-1}, with the dashed contour line as in Fig. 4.

Figs. 6 and 7 were common to each of the cases, although one occurred during EN, another during LN, and the other three during the neutral phase of ENSO. This seems to indicate that in the case of 1982, the peak of August in the anomaly contribution of the upper and middle basins was not related to EN. This hypothesis is reinforced by the fact that during the winter (0) of EN there are not significant precipitation anomalies over the Paraguay basin (Grimm et al. 2000). This may also be the case of the major discharges during January and February of EN phases, as significant positive anomalies over the Paraguay River basin during EN phase are only important during the autumn (0) and the autumn (+) (Grimm et al. 2000). For this reason it is likely that, as in the case of August 1982, the coincidence of the summer peaks of 1912 and 1995 with EN events could be fortuitous. This claim does not contradict the statistical results of section 4, as six of the greatest anomalies had a direct relationship with EN phase. Thus, these cases together with a few other casual concurrent cases add to the number of nine cases that only can be attributed to chance with a very low probability.

5. Summary and concluding remarks

Most of the major discharges of the Paraguay River at Asunción peak between May and July, in phase with the maximum of the annual cycle. However, although the top discharge anomalies also occurred during the May to July period, the other major anomalies peaked at almost every time of the year, responding to different climate forcings.

During the twentieth century, the major discharges of the Paraguay River originated in the upper and middle Paraguay basins and their occurrence did not depend on the water storage of the Pantanal. Not only did the discharge anomalies at the Pantanal outlet not contribute substantially to the respective anomalies in Asunción discharges, but neither were they significantly correlated with the contribution from their upper and middle basins to the Paraguay River discharge. This implies that the climate forcings of the major discharge contributions were different in both sectors of the Paraguay basin. In fact, while most of the major discharge contributions of the upper and middle Paraguay River occurred during El Niño periods, most of the major discharges at the Pantanal outlet occurred in the neutral phases of the ENSO. This reflects the fact that the Pantanal lies in a transition region regarding the impact of ENSO in rainfall, since to the north, in the Amazon basin, there is a predominant LN–wet and EN–dry relationship (Ropelewski and Halpert 1996; Souza et al. 2000) and the opposite holds to the south in most of the Plata basin (Grimm et al. 2000).

Southeastern South America is one of the extratropical regions whose climate is affected by ENSO events. However, the EN signal does not stay along its phase, but has a seasonal pattern, which has also spatial variability. The two most significant signals of El Niño events on rainfall were in spring (0) south of the Paraguay basin and in autumn (+) over the area surrounding the common border between Brazil, Argentina, and Paraguay (Fig. 4). This signal is responsible for the largest floods of the Paraná River in the Argentine territory (Camilloni and Barros 2003).

About half of the major discharge anomalies of the upper and middle basin contribution to the Paraguay River occurred during EN phase of the ENSO, and although in a few cases this could have been a fortuitous concidence, there is little probability that the observed rate of major discharges during EN phase could happen by chance. The EN signal was more unambiguous in the five cases that occurred during the autumn (+) as they rank between the top discharges. The composite of these cases shows a tropospheric wave train from the equatorial Pacific that dominates the southern South America upper-tropospheric circulation enhancing the subtropical jet and the cyclonic vorticity advection over the Paraguay River basin. Consistent with this anomaly circulation pattern, the precipitation pattern had a positive anomaly of more than 80 mm month^{-1} centered in the Alto Paraná basin that extends over the eastern part of the upper and middle Paraguay basins. Except for the autumn (0) case, the other major discharge anomalies that occurred in EN phase, either in winter (0) or in summer, cannot be attributed to EN forcing. In these seasons, there is not a significant EN signal over most of southeastern South America and over the Paraguay River basin in particular (Grimm et al. 2000).

Despite the clear EN signal, about half of the major discharge anomalies were not related to the ENSO phase, as they occurred equally during LN or the neutral phases. Of these cases, the five that occurred during wintertime share common circulation and precipitation features. The average fields from April to August of all these cases had an almost barotropic tropospheric pattern at high latitudes with a very deep cyclonic anomaly between 120° and 160°W and an anticyclonic anomaly centered at the southern tip of South America. This pattern is indicative of frequent blocking conditions in the circulation over southern South America, which favor the deviation of the frontal and cyclonic perturbations entering the continent more to the north. Thus, these cases present precipitation anomalies in a broader region that the Paraguay River basin. Consistent with this displacement of the perturbation tracks, there is a strong negative precipitation to the south of this basin, while the positive anomalies stretch in a band from Bolivia to the Brazilian coast including almost the whole Paraguay River basin. These anomalies, while not as important as in the autumn (+) case, represent a precipitation considerably exceeding the mean evaporation of these months.

The major discharge anomalies that occurred in winter illustrate that in southeastern South America it is possible to identify sources of interannual climate variability affecting the surface hydrology other than ENSO or the chaotic nature of the atmosphere.

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