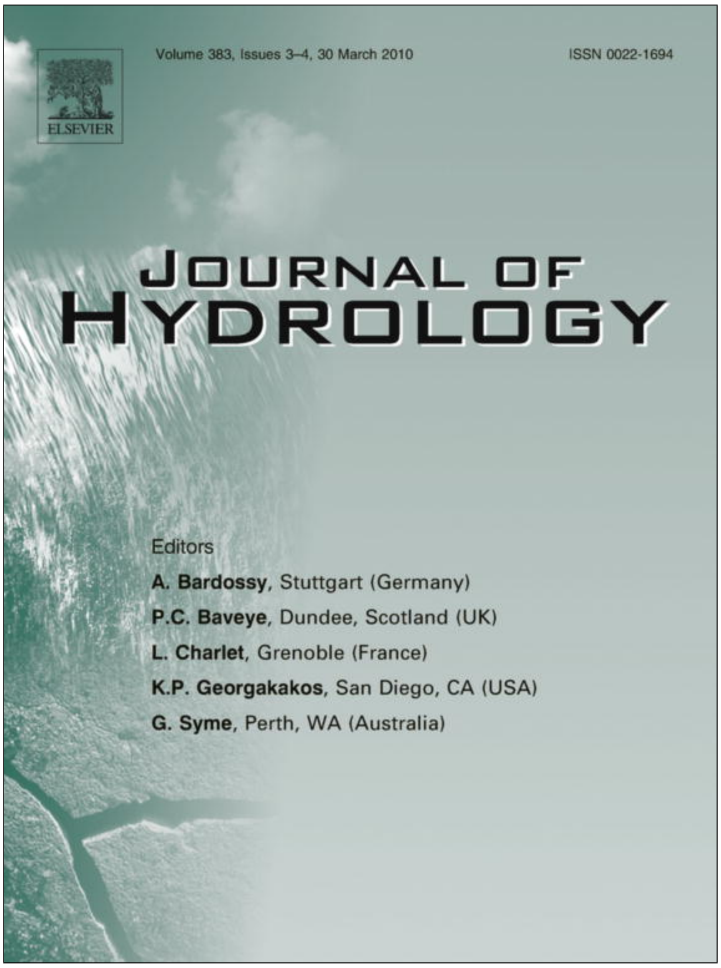
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ENSO-triggered exceptional flooding in the Paraná River: Where is the excess water coming from?

Andrea I. Pasquini *, Pedro J. Depetris

Centro de Investigaciones en Ciencias de la Tierra (CICTERRA/CIGeS), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET/Universidad Nacional de Córdoba), Av. Vélez Sarsfield 1611, X5016CGA, Córdoba, Argentina

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SUMMARY

The Paraná River has been increasing its annual flow during the last ~30 years. The relative contribution of its major tributaries (i.e., the upper Paraná and Paraguay rivers) is uneven in as much as the Paraguay is increasing its annual discharge at a higher pace than the upper Paraná does. Contrastingly, the upper Paraná has been increasing significantly its flow during the second half of the year (i.e., historical low water period) whereas the Paraguay River has been amplifying its flow throughout the hydrological year. The variability of $\delta\ ^{18}O$ measured in the Paraná River middle reach tends to follow Paraguay's relative contribution to Paraná's total discharge. A simple model built on the basis of the mean $\delta\ ^{18}O$ signature of rainfall (Global Network of Isotopes in Precipitation) shows significant coherency with the relative contribution time series during non-El Niño periods but it is necessary to invert the mean isotopic values in precipitation during the occurrence of a major ENSO event (i.e., assume that $\delta\ ^{18}O$ in upper Paraná River water becomes more negative than usual) to improve the resemblance to the observed variability.

Introduction

The teleconnection existing between ENSO occurrences in the Equatorial Pacific Ocean and anomalous hydrological behavior over a significant portion of South America has been the object of extensive research for many years. The correlation found in the 1920s by Sir Gilbert Walker's group between surface pressure in Australia and the Paraná River discharge at Rosario, Argentina, is a good example of such allegation (e.g., Bliss, 1928). During the last 20 years the knowledge on such teleconnection was significantly broadened (e.g., Kousky et al., 1984; Ropelewski and Halpert, 1987; Depetris et al., 1996; Amarasekera et al., 1997; Robertson and Mechoso, 1998; Boulanger et al., 2005; García and Mechoso, 2005; Pasquini and Depetris, 2007) and more evidence was found on the linkage between ENSO dynamics and the hydrology of the Río de la Plata drainage basin (i.e., the added drainage basin areas of the Paraná and the Uruguay rivers).

In 1982–1983, the Southern Oscillation Index (SOI) – one of the most widely used indicators to assess ENSO's strength – dropped down to −3.46 in February 1983. Such markedly negative index signified a robust El Niño event, which in turn determined a record discharge of over 60,000 $m^3\ s^{-1}$ in June 1983, in the Paraná River at the Corrientes gagging station, about 1200 km upstream from Paraná's mouth.

In earlier works we have evaluated discharge trends and ENSO-linked flooding periodicities in the Paraná and Uruguay drainage basins (e.g., Depetris et al., 1996; Pasquini and Depetris, 2007). In this occasion our primary objective is to analyze the relative water contributions of Paraná's main upper tributaries, seeking to establish if they are increasing their historical water supply at a similar rate. Preliminary data indicated that this may not be the case. Secondarily, we wish to examine the association between the mentioned relative discharge contributions and the response triggered in stable isotopes determined in the Paraná's middle course during strong ENSO episodes.

Study area

The Paraná River (drainage area, ~2.8 × $10^6\ km^2$) has widely differing headwaters that sometimes exhibit contrasting dynamics: from Andean sources close to South America's Pacific active margin, in the Pilcomayo and Bermejo upper catchments (~65°W), to the tropical headwaters placed at the Serra dos Preneos (~45°W), close to the Atlantic passive margin. With headwaters at the Gran Pantanal (one of the largest wetlands in the

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* Corresponding author. Tel.: +54 (0) 351 4344983; fax: +54 (0) 351 4333199.
E-mail addresses: apasquini@com.uncor.edu (A.I. Pasquini), pdepetris@com.uncor.edu (P.J. Depetris).

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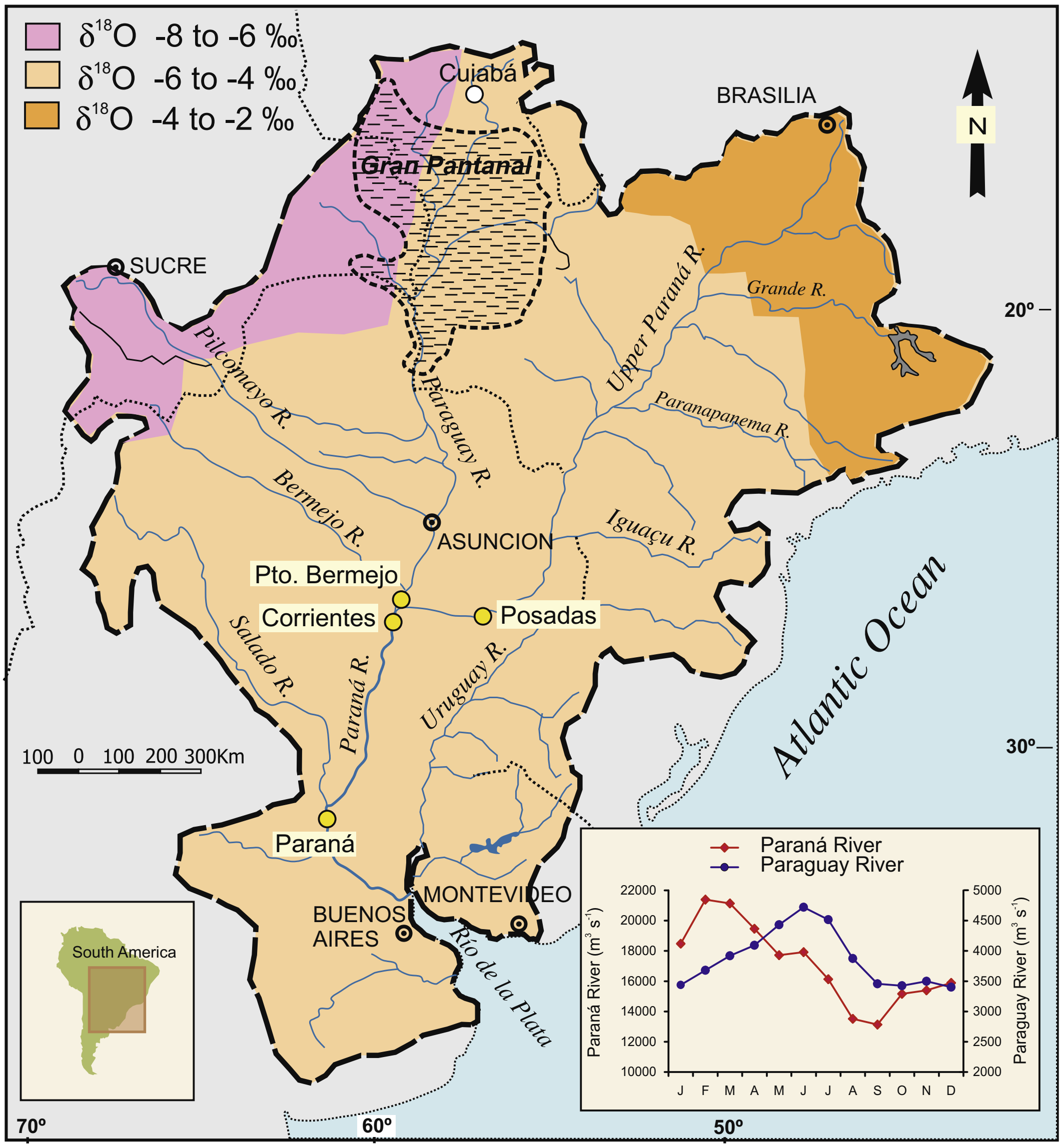

Fig. 1. Subset of South America's mean isotopic distribution map (Aggarwal et al., 2007) depicting the Río de la Plata drainage basin ($\sim 3.1 \times 10^6$ km^2). $\delta\ ^{18}O$ (‰) areas in the map are long-term precipitation annual averages from IAEA's Global Network of Isotope in Precipitation (GNIP), where the map is available (http://nds121.iaea.org). Inset shows historical monthly mean discharge in the Paraná River (at Corrientes) and Paraguay River (at Puerto Bermejo). Hydrological data was supplied by Argentina's Subsecretaría de Recursos Hídricos. Capitals and cities of South American countries are included as geographical references.

world, at ~15°S and ~55–60°W, Fig. 1) that exerts a discernible modulating effect (Junk and Nunes de Cunha, 2005), the Paraguay River runs with a N–S direction, joining the Paraná River at Corrientes, which continues southward bound in a middle and lower course that splits the Paraná drainage in two uneven halves (Pasquini and Depetris, 2007).

The Paraná River is the main contributor to the riverine water budget of the Río de la Plata drainage basin (Fig. 1). On the average, it currently delivers ~530 km^3 of water per year to the Río de la Plata estuary, of which ~73% is supplied by Paraná's upper catchments (i.e., including the Iguaçú River), ~20% by the Paraguay River and nearly 7%, jointly by the rivers draining South America's mountainous backbone (i.e., Bermejo, Pilcomayo, and Salado rivers) (e.g., Pasquini and Depetris, 2007). These relative contributions are, however, mean annual approximations, and the year-to-year hydrological functioning is quite variable, particularly when the system is subjected to anomalous episodes, like the ENSO. During El Niño-triggered flooding – which in the Paraná River normally occurs in phase with the annual high water period – the upper tributaries do not supply a constant relative flow contribution to the river's main stem. The ENSO also has a limited impact on the coastal zone. Worth mentioning is the fact that, during El Niño events, the Río de la Plata does not produce an anomalous northeastward plume extension in the Atlantic Ocean – as would be expected in a large outflow event – but spreads offshore instead (Piola et al., 2005).

The summer circulation over South America is dominated by a monsoonal system, whose major seasonal feature is the South Atlantic Convergence Zone (SACZ), placed along the north-eastern boundary of the Río de la Plata drainage basin (e.g., Robertson and Mechoso, 2000). Another significant feature in the regional climatic control is a low-level northerly/northeasterly jet that flows east of the Andes, and transports moisture along the corridor placed between the Andes and the Brazilian *altiplano* (e.g., Wang and Fu, 2004). As a consequence of these continental climatic features, the mean annual rainfall is unevenly distributed over the Paraná River drainage basin. Maximum recorded precipitation (2400 mm y^{-1}) occurs along the eastern edge of the basin and over the Iguaçu drainage basin. Rainfall decreases (400–800 mm y^{-1}) towards the western edge of the basin, along the 60–65°W strip. In general, runoff mimics rainfall distribution, with high values along the basin's NE corner (700–800 mm y^{-1}) and in the Bermejo and Pilcomayo upper catchments (~500 mm y^{-1}). Along the Paraná upper and middle course, mean runoff is ~300 mm y^{-1}.

Human activities affect river flow in many ways: directly, through dams or, indirectly, through the use of the land. Built to foster development, the upper Paraná River, for example, has in operation about 130 reservoir dams (dam height >10 m), of which 14 are considered "major dams" (dam height >150 m) (Ravenga et al., 1998) that modulate its discharge and sequestrate sediments. Neither the Paraguay nor its tributaries have major dams in their respective headwaters.

Data and methods

Hydrological data were obtained from Argentina's Subsecretaría de Recursos Hídricos, which performs the quality control and maintains the available hydrological information in the public domain (www.hidricosargentina.gov.ar). Table 1 shows the geographic location of the used hydrological stations, including the length of the discharge records. The $\delta^{18}O$ series was reported elsewhere (Depetris et al., 1996). It consists of 45 determinations (Table 2) (analytical uncertainties of ±0.1‰) performed in samples collected between March 1981 and November 1984 at the city of Paraná (described as Santa Fé in Depetris et al., 1996), located about 600 km upstream from the mouth.

To assess the significance of trends in annual river discharge, we have employed the Mann–Kendall test – also known as Kendall's tau – (Mann, 1945; Kendall, 1975), based on Sen's non-parametric method, which is used to estimate the true slope of an existing trend such as flow change per unit time period (in this case a year). Hence, Sen's estimator of slope is the median of N values of the examined variable (http://pubs.usgs.gov/twri/twri4a3/).

The seasonal Kendall test (Hirsch et al., 1982) was used to examine monthly trends. Both – the Mann–Kendall and the seasonal Kendall tests – are non-parametric tools used to detect monotone trends in time series (e.g., Burn and Hag Elnur, 2002; Yue et al., 2002). On the other hand, the seasonal Kendall test has been identified as one of the most robust techniques available to detect and estimate linear trends in environmental data (Hess et al., 2001). To investigate periodic behavior in the Paraguay/Paraná discharge ratio, we have used the Fourier spectral analysis. As it is widely known, this method uses sine and cosine base functions and reveals in a signal what spectral component is present (Lau and Weng, 1995).

Table 2
Sampling date, data used in the isotopic model, and measured and modeled $\delta^{18}O$ in Paraná River. Shaded area indicates the ENSO period (see text for explanation).

Sample date (d.m.y)	SOI	$\delta^{18}O_{Pay}$[a]	$\delta^{18}O_{ParC}$[a]	$\delta^{18}O$[b]	$\delta^{18}O^{*}$[c]
18.03.81	−2.01	−7	−4	−4.60	−5.13
08.04.81	−0.60	−7	−4	−4.42	−5.26
10.06.81	1.28	−5	−3	−3.70	−3.75
24.06.81	1.28	−5	−3	−4.03	−3.73
15.07.81	0.87	−5	−3	−4.15	−3.76
18.08.81	0.40	−5	−3	−4.15	−3.68
02.09.81	0.52	−5	−3	−4.14	−3.71
16.09.81	0.52	−5	−3	−3.92	−3.69
02.10.81	−0.71	−5	−3	−3.86	−3.63
19.10.81	−0.71	−5	−3	−3.58	−3.49
03.11.81	0.07	−5	−3	−3.71	−3.44
18.11.81	0.07	−7	−4	−3.88	−3.36
30.11.81	0.07	−7	−4	−3.70	−3.40
22.12.81	0.41	−7	−4	−5.14	−4.54
11.01.82	0.87	−7	−4	−5.25	−4.55
26.01.82	0.87	−7	−4	−4.78	−4.63
24.03.82	0.05	−7	−4	−5.94	−4.57
06.04.82	−0.46	−3	−6	−6.76	−5.48
23.04.82	−0.46	−3	−6	−6.81	−5.23
26.05.82	−0.74	−3	−6	−6.42	−5.09
23.06.82	−2.49	−3	−6	−6.13	−5.26
14.07.82	−1.89	−3	−6	−5.63	−5.31
06.08.82	−2.66	−3	−6	−5.11	−5.11
25.08.82	−2.66	−3	−6	−5.14	−5.00
22.09.82	−2.12	−3	−6	−4.88	−4.84
27.10.82	−2.20	−3	−6	−3.71	−4.26
24.11.82	−3.25	−3	−6	−4.19	−5.41
15.12.82	−2.48	−3	−6	−4.83	−5.43
28.12.82	−2.48	−3	−6	−4.71	−5.36
03.02.83	−3.46	−3	−6	−4.93	−5.42
23.02.83	−3.46	−3	−6	−5.00	−5.53
11.03.83	−3.25	−3	−6	−5.30	−5.55
14.04.83	−1.41	−3	−6	−5.53	−5.36
03.05.83	0.79	−3	−6	−5.20	−5.49
03.06.83	−0.58	−3	−6	−5.06	−5.38
23.08.83	−0.37	−5	−3	−3.81	−3.54
21.09.83	0.91	−5	−3	−3.53	−3.48
26.10.83	0.34	−5	−3	−3.63	−3.32
06.12.83	−0.17	−7	−4	−4.30	−4.54
15.02.84	0.43	−7	−4	−5.28	−4.47
06.04.84	0.39	−7	−4	−5.50	−4.81
30.05.84	−0.03	−7	−4	−5.04	−5.10
01.08.84	0.10	−5	−3	−4.11	−3.65
25.09.84	0.17	−5	−3	−3.77	−3.49
29.11.84	0.12	−5	−3	−3.80	−3.56

[a] See text for explanation.
[b] River water values measured in Paraná R (analytical uncertainties of ±0.1‰).
[c] River water values modeled in Paraná R.

Results and discussion

Analysis of water sources

In earlier works (Pasquini and Depetris, 2007; Depetris and Pasquini, 2008) we have shown by statistical means, that water discharges of most of Paraná's headwaters (i.e., the upper Paraná and the Paraguay) have been increasing significantly during the last 20–30 years. Interestingly, the seasonal Kendall test showed that flow increase was mostly accounted for by low discharge months (i.e., austral winter months for the Paraná) (Pasquini and Depetris, 2007).

Now, we decided to compare the discharge of both, the upper Paraná and the Paraguay at their meeting point, near the Argentine city of Corrientes (Fig. 1). In order to do this, we used the nearly 100-year long time series (1910–1998) built with the ratio $Q_{ym\text{-}Pay}/Q_{ym\text{-}ParC}$ where $Q_{ym\text{-}Pay}$ is the annual mean discharge of the Par-

Table 1
Name, location and record period of studied hydrological stations (see geographical location in Fig. 1).

River	Gage station	Latitude (S)	Longitude (W)	Record period	No. of years	No. of data[a]
Paraguay	Puerto Bermejo	26°56′	58°30′	1910–1998	88.5	1051
Paraná	Posadas	27°27′	55°48′	1901–2000	99.5	1197
Paraná	Corrientes	27°28′	58°50′	1904–2003	99.5	1196

[a] Monthly mean discharge data.

aguay River at Puerto Bermejo, and $Q_{\text{ym-ParC}}$ is the mean annual discharge of the Paraná at Corrientes. The Mann–Kendall test (Mann, 1945) of this series (Fig. 2a) clearly shows a significant positive slope (Sen's slope 5.6×10^{-4} m^3 s^{-1} per year, $p < 0.01$).

We chose, then, to look at the other branch, the one formed by the upper Paraná before joining the Paraguay River. Similarly, we defined the nearly 100-year long time series (i.e., the same length as the one examined previously) built with the ratio $Q_{\text{ym-ParP}}/Q_{\text{ym-ParC}}$ where $Q_{\text{ym-ParP}}$ is the annual mean discharge of the Paraná River at Posadas. Fig. 2b shows the Mann–Kendall test for the above discharge ratio. In this case, Sen's slope (4.3×10^{-4} m^3 s^{-1} per year, $p < 0.1$) is less steep and has a lower significance level, which means that, in relative terms, the flow rate in the Paraguay is actually increasing faster than the one recorded in the upper Paraná. It is interesting to mention that if we extend the length of the latter series (i.e., 1904–2000), Sen's slope is not statistically significant.

Fig. 2c shows the results of the seasonal Kendall analysis (Kendall, 1975) of Paraná and Paraguay rivers monthly mean discharge time series. While the Paraguay River maintains significantly increasing discharges throughout the year, the Paraná at Corrientes only shows a significant increase during the second half of the year, (i.e., June–December), for the period of low and intermediate flow months (i.e., austral winter and spring). More detail is obtained when Paraguay's and upper Paraná's relative discharge contributions are defined in terms of monthly mean discharges (Fig. 2c). In this case we used similar ratio series instead, as they were defined above: $Q_{\text{mm-Pay}}/Q_{\text{mm-ParC}}$ and $Q_{\text{mm-ParP}}/Q_{\text{mm-ParC}}$, where $Q_{\text{mm-Pay}}$ is the deseasonalized monthly mean discharge of the Paraguay at Puerto Bermejo, $Q_{\text{mm-ParC}}$ is the equivalent series for the Paraná River at Corrientes, and $Q_{\text{mm-ParP}}$ is the same for the Paraná River at Posadas. The seasonal Kendall analysis of such series (Fig. 2c) shows that the relative contribution of the Paraguay is amplified significantly in the first half of the year, during its increasing flow stage (i.e., January–May, Fig. 1, inset). On the other hand, the Paraná's relative contribution is statistically significant between May and August, during the period of decreasing flow (Fig 1, inset).

It remains for further analysis if the observed upper Paraná's relative contribution to the total riverine flow is somehow linked to human-made influence, like the proliferation of dams observable upstream from its encounter with the Paraguay River.

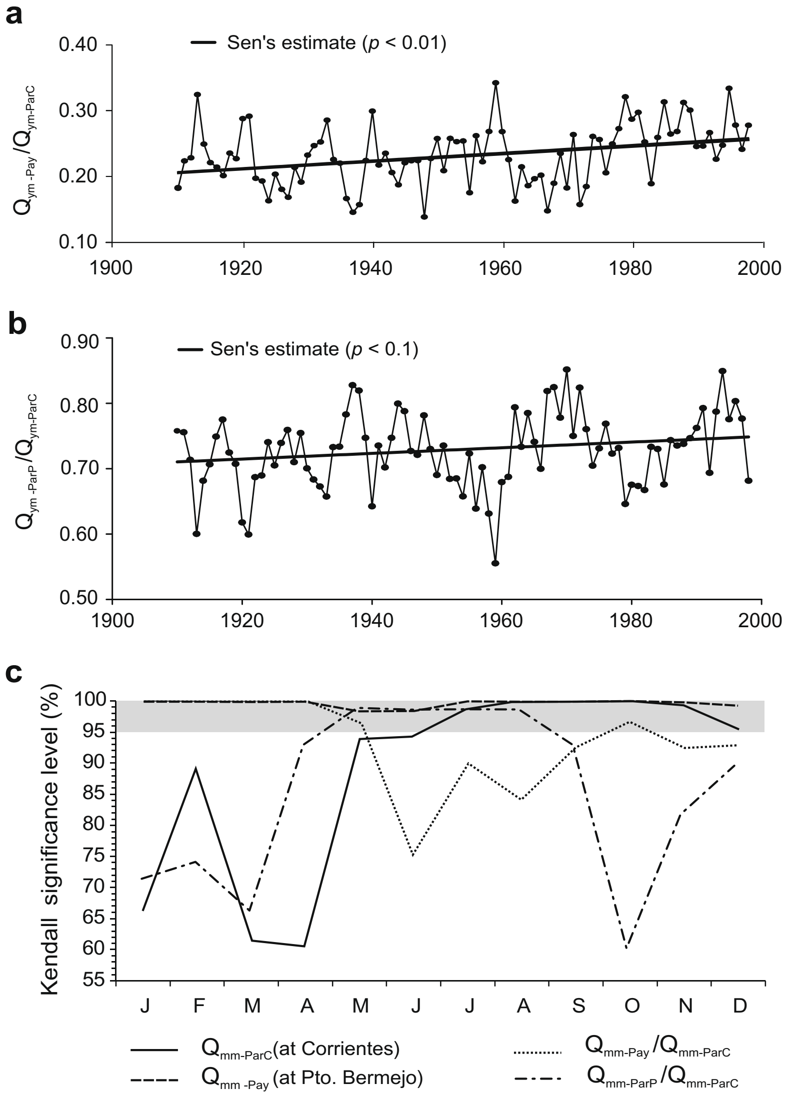

Fig. 2. (a) Mann–Kendall test applied on the Paraguay River's relative contribution ($Q_{\text{ym-Pay}}/Q_{\text{ym-ParC}}$ hydrological series); (b) the same as (a) for the upper Paraná River's relative contribution ($Q_{\text{ym-ParP}}/Q_{\text{ym-ParC}}$ hydrological series); (c) seasonal Kendall test applied on relative contribution hydrological series (i.e., $Q_{\text{mm-Pay}}/Q_{\text{mm-ParC}}$ and $Q_{\text{ym-ParP}}/Q_{\text{ym-ParC}}$), and on $Q_{\text{mm-Pay}}$ (Paraguay River monthly mean discharge series at Puerto Bermejo), and $Q_{\text{mm-Par}}$ (Paraná River monthly mean discharge series at Corrientes); the shaded area corresponds to values with a 95% significance level or higher.

In view that the relative contribution of the Paraguay River is increasing at a higher rate than the upper Paraná River does, we decided to analyze the periodic behavior of this contribution (i.e., Paraguay River monthly relative contribution series, $Q_{mm\text{-}Pay}/Q_{mm\text{-}ParC}$). To do this, we used spectral analysis (Fourier power spectrum). Fig. 3a shows the periodogram of the analyzed series, which exhibits several significant peaks with inter-annual frequencies that are compatible with ENSO periodicity. To complete our analysis, we sought out the coherence between the Paraguay River monthly relative contribution series (i.e., $Q_{mm\text{-}Pay}/Q_{mm\text{-}ParC}$) and the SOI (Fig. 3b), which reveals statistically significant squared coherencies in the inter-annual ENSO frequency range.

The isotopic signature

The International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO) have operated the Global Network of Isotopes in Precipitation (GNIP) for over 45 years (Aggarwal et al., 2007). The support supplied by such observational network and the study of Andean ice cores indicate that $\delta\ ^{18}O$ in rainfall is significantly affected by the ENSO over a considerable portion of South America (Hoffmann, 2003; Vuille et al., 2003a,b). In a recent contribution, Vuille and Werner (2005) analyzed the coupled influence of ENSO phenomena and the South American Summer Monsoon (SASM) over the $\delta\ ^{18}O$ signature in rainfall. Observational data collected through GNIP and the application of Atmospheric General Circulation Models (AGCMs) show that intense monsoon seasons result in more depleted, lighter isotopic values in the rainfall falling over the Amazon River drainage basin, SE of South America and the central Andes. The phenomenon, frequently observed in tropical regions, is consistent with the "amount effect" (i.e., rainwater becomes more depleted in heavy stable isotopes as precipitation progresses). However, when the SASM signal is decomposed into the fraction of variance that is explained by ENSO and the residual monsoon component, the correlation between $\delta\ ^{18}O$ signature in precipitation and the El Niño 3.4 index is almost the opposite compared to the correlation with the SASM in most of South America. (Vuille and Werner, 2005). Hence,

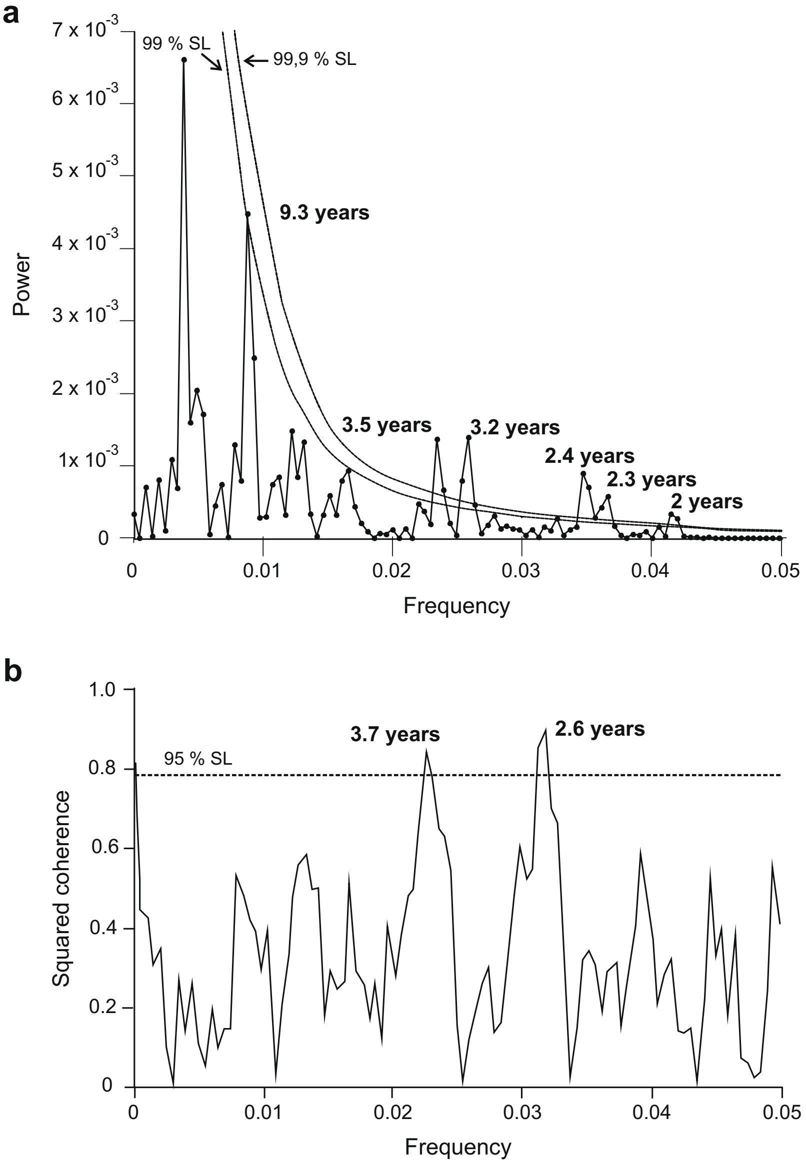

Fig. 3. (a) Filtered Fourier power spectrum of the $Q_{mm\text{-}Pay}/Q_{mm\text{-}ParC}$ series; an autoregressive coefficient (i.e., the spectrum is produced by autoregressive modeling rather than a transform) of 0.99 was used to model red noise critical limits (i.e., noise power decreases with increasing frequency); Critical limits (significance levels (SL) are indicated in each case) were used to determine the statistical significance of the largest peaks in the power spectrum. See text for additional explanations; (b) squared coherence of $Q_{mm\text{-}Pay}/Q_{mm\text{-}ParC}$ series and the Southern Oscillation Index (SOI). Note the significant squared coherence ($p < 0.05$) at El Niño return periods.

during El Niño years, δ ^{18}O in precipitation falling over Paraguay's headwaters is heavier in isotopic terms. Over the southeastern part of the continent (i.e., the Paraná River upper basin), however, predominates the lighter signal of the residual monsoon component (Vuille and Werner, 2005).

Panarello and Dapeña (2009) published a relatively long series (10 years) of monthly δ ^{18}O and δ ^{2}H determinations measured at the lower Paraná River, near the city of Buenos Aires. They failed to obtain a significant correlation between the stable isotopes measured in river water and ENSO indices. They found, however, a coherent relationship between the global-SST ENSO index and the so-called "deuterium excess", defined by Dansgaard (1964) as $d = \delta^2H - 8\ \delta^{18}O$. The deuterium excess can be used to identify vapor source regions; humidity relative to saturation at sea surface temperature and wind speed are the major controlling factors. When the source conditions of the water vapor change as during El Niño events, *d* is larger (Gat, 2005). The higher diffusivity for $^2H^1H^{16}O$ as related to $^1H^1H^{18}O$ results in a higher *d*. Panarello and Dapeña (2009) also argued that during El Niño events, more recycled water vapor from the Amazon basin may be trapped and transported southward. Such vapor is considerably enriched in δ ^{2}H, thus determining the observed higher *d* values during the 1997–1998 El Niño event (Panarello and Dapeña, 2009).

By using the map published by Aggarwal et al. (2007), which is also available in the GNIP web site, we prepared a map restricted to the Río de la Plata drainage basin (Fig. 1), which includes the mean distribution of long-term annual average of δ ^{18}O (‰) in precipitation. Fig. 1 shows that, on the average, rainfall heavier in isotopic terms, falls over the NE corner of the Río de la Plata drainage (i.e., the Paraná headwaters). In Paraguay's upper catchments, and further towards the Andean range, the long-term annual average of δ ^{18}O in rainfall becomes more negative.

In order to contribute to an improved understanding of the dynamics of stable isotopes in the ENSO-affected Paraná River, we employed a series of δ ^{18}O values reported in an earlier publication (Depetris et al., 1996). The isotopic series was plotted along with the series built with the $Q_{\text{dm-Pay}}/Q_{\text{dm-ParC}}$ ratio, where $Q_{\text{dm-Pay}}$ is the daily discharge measured at Puerto Bermejo, in the Paraguay River, and $Q_{\text{dm-ParC}}$ is the equivalent gage reading measured in the Paraná River at Corrientes (Fig. 4a). Hence, the series shows the relative contribution of the Paraguay River to the middle or lower Paraná reaches (Fig. 4a). Its inspection shows that, after the onset of the 1982–1983 El Niño-triggered flood, the Paraguay River relative contribution to the middle and lower Paraná discharge reached almost 60%. This is caused not only by Paraguay's discharge increase but also by a synchronous discharge decrease in the Paraná (Fig. 4b).

There is a discernible coherency between both series, $Q_{\text{dm-Pay}}/Q_{\text{dm-ParC}}$ and the measured δ ^{18}O, (Fig. 4a) that increases noticeably if one displaces one series with respect to the other in order to account for the water time-of-travel between rainfall at the headwaters and the Paraná gage site (about 600 km upstream from Paraná's mouth), where the stable isotopes were measured. Such water transit time was estimated by Panarello and Dapeña (2009) in roughly 90 days. Fig. 4a suggests that δ ^{18}O signal in the middle and lower Paraná stretch is basically controlled by the relative contribution of both, the Paraguay and Paraná River water, even during a very strong ENSO event, such as the one observed in 1982–1983.

To test our assumptions we built a very simple mixing model with a mass-balance equation: $\delta\ ^{18}O_i^* = (Q_{\text{dm-Pay}}/Q_{\text{dm-ParC}})_i\ \delta\ ^{18}O_{\text{Pay}} + (1 - (Q_{\text{dm-Pay}}/Q_{\text{dm-ParC}})_i\ \delta\ ^{18}O_{\text{ParC}})$, where $\delta\ ^{18}O_i^*$ (in ‰) is the modeled concentration for the Paraná River water at Paraná for the *i*th day; $(Q_{\text{dm-Pay}}/Q_{\text{dm-ParC}})_i$ is the already defined Paraguay/Paraná dis-

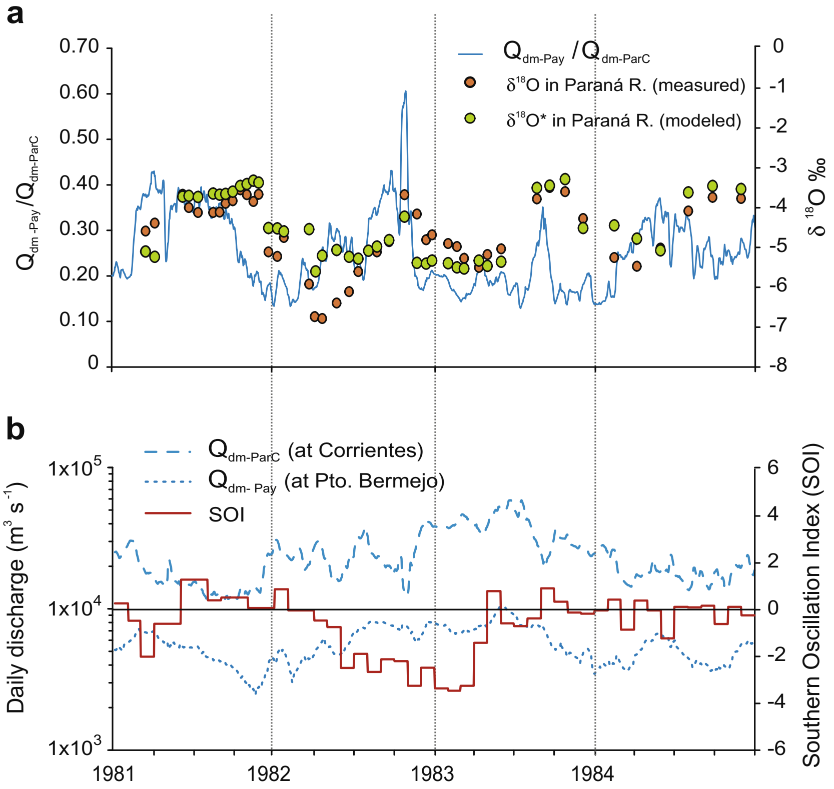

Fig. 4. (a) $Q_{\text{dm-Pay}}/Q_{\text{dm-ParC}}$ ratio series (not deseasonalized) plotted along with measured (in the Paraná River, at Paraná, 600 km upstream the mouth) and modeled δ ^{18}O; (b) $Q_{\text{dm-Pay}}$ (not deseasonalized) (at Puerto Bermejo) and $Q_{\text{dm-ParC}}$ (not deseasonalized) (at Corrientes) discharge series plotted along with the Southern Oscillation Index (SOI); note the beginning (~April 1982) and the end (~April 1983) of the 1982–1983 El Niño event. High discharges at the Paraná and Paraguay rivers persist several months after the ending of the ENSO event in the Pacific Ocean.

charge ratio for the *i*th day; δ $^{18}O_{Pay}$ and δ $^{18}O_{ParC}$ are the stable isotope values in rainfall falling over the Paraguay and the Paraná drainage basins, respectively, obtained from the mean isotopic data plotted on the GNIP map (Aggarwal et al., 2007). To assign the corresponding stable isotope values (i.e., δ $^{18}O_{Pay}$ and δ $^{18}O_{ParC}$), we followed the subsequent rationale: (i) we used the long-term annual isotopic signature corresponding to each headwater, as depicted in Fig. 1; (ii) the values assigned to δ $^{18}O_{Pay}$ and δ $^{18}O_{ParC}$ varied somewhat according to seasonality; values for summer where lighter in isotopic terms than those used for winter, following the published GNIP records for South America; and (iii) the values for δ $^{18}O_{Pay}$ and δ $^{18}O_{ParC}$ during the 1982–1983 ENSO event were inverted, according with the findings published by Vuille and Werner (2005), already mentioned above. Therefore, δ $^{18}O_{Pay}$ mean value was assumed to be −7 and δ $^{18}O_{ParC}$ mean was −4 for the period December–May, and −5 and −3, respectively, were the means for the period June–November. For the El Niño event period (i.e., since April 1982 until June 1983, to account for the lag between ENSO and high discharges), the mean values were inverted and δ $^{18}O_{Pay}$ was −3 and δ $^{18}O_{ParC}$ was −6, thus following the findings of Vuille and Werner (2005).

Table 2 shows the data employed for the model and the resulting isotopic series. The inversion in the precipitation isotopic values alluded above is discernible in the shaded area of the table: δ $^{18}O_{ParC}$ are assumed as more negative than δ $^{18}O_{Pay}$ during the ENSO period. In the same table, seasonal changes in isotopic composition are indicated by horizontal separating lines.

Note that there is a reasonable linear correlation ($r = 0.76$, $N = 45$, $p < 0.05$) between measured and modeled δ ^{18}O. Upon inspection, it is also noticeable that the correlation coefficient slightly improves ($r = 0.79$, $N = 27$, $p < 0.05$) during non-El Niño periods. Although the model reproduces well the observed isotopic features for most periods, it clearly fails to mimic other features like the pronounced isotopic depletion in Paraná's water observed at the onset of the 1982 ENSO event. We assume that this phenomenon may be attributable to atmospheric disturbances that altered temporarily the sources of water vapor at the ENSO onset, which our simple model could not reproduce.

Conclusions

Both, the upper Paraná and the Paraguay rivers have been increasing their respective discharges during the last decades (e.g., Pasquini and Depetris, 2007; Depetris and Pasquini, 2008). Our current analysis indicates, however, that the Paraguay is increasing its flow at a faster pace than the upper Paraná does, rising significantly its water contribution to the middle and lower Paraná River discharge. Moreover, although the Paraná is increasing significantly its discharge in the second half of the year, the seasonal Kendall ($Q_{mm\text{-}Pay}/Q_{mm\text{-}ParC}$) clearly shows that Paraguay's relative contribution to the overall flow is distinctly discernible during the first half of the year. Now, is such increased flow somehow linked to El Niño occurrences? The answer to this question appears affirmative because the harmonic analysis of the $Q_{mm\text{-}Pay}/Q_{mm\text{-}ParC}$ ratio series shows significant coherence peaks in the ENSO inter-annual frequency range (i.e., 3.7 and 2.6 years).

The stable isotopic signature of the middle and lower Paraná River water (δ ^{18}O) seems to be considerably tied to the relative contribution of each individual headwater, namely, the upper Paraná and the Paraguay drainage basins. Each river basically delivers water which carries the mean isotopic signal of rainfall determined through GNIP, particularly so during non-El Niño periods. In contrast, during El Niño condition, each river seems to stop carrying the GNIP-determined mean isotopic signal, which in such occasions appears to be reversed. Hence, the Paraná delivers a δ ^{18}O signal that is isotopically lighter and the Paraguay, one that is heavier than usual. A simple mass balance model built following the mentioned reasoning roughly explains 76% of the total variance (79% during non-ENSO periods), thus suggesting that local variability (e.g., evapotranspiration in the flood plain and active water exchange with the main channel) also plays a significant role in defining the final isotopic signature that ultimately reaches the Atlantic Ocean. Hence, we feel that our simple model using stable isotopes determined in river water reinforces the notion proposed by Vuille and Werner (2005) which used GNIP data and the high-resolution version of the ECHAM-4 stable isotope model (Hoffmann et al., 1998) to asses the relationship between continental circulation patterns and stable isotopic signature in rainfall.

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