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Further evidence of changes in the hydrological regime of the River Paraguay: part of a wider phenomenon of climate change?

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Abstract

Analysis of flow measured at 20 sites, rainfall measured at 36 sites, and a 95-year record of water-level at one site in the basin of the River Paraguay (area $1095 \times 10^3\ \text{km}^2$) showed that the flow regime during the approximate period 1960–1970 differed substantially from the flow regime both before and after. The long record of Ladario water-levels suggested that the changes between one period and the next were considerably abrupt, and that the periods differed not only in terms of mean water-levels but also in terms of the year-to-year correlational structure within the record. Despite the fragmentary nature of rainfall records from 36 sites, an explanation for the increased flows since 1970 was found in the increases of rainfall, as assessed in terms of the frequency of annual rainfalls more than the long-term mean rainfall. There was some degree of consistency in the change of rainfall pattern across the Paraguay basin as a whole. A detailed examination of daily rainfall characteristics at two gauges where records were fairly complete showed that during the 1960–1970 period, when river flows were low, dry spells were more persistent and, on days when rain did fall, the amounts of rain were generally smaller. The results obtained were compared with results obtained by other researchers using flow records from the Rivers Paraguay, Paraná, Negro and Uruguay in the la Plata basin, and rainfall records from other parts of South America. There is now strong evidence of changes in the runoff regime of the la Plata basin during the last 40 years, not all of which can be attributed to land-use change, as there is complementary evidence of change in rainfall regime. The results were also compared with findings from the Congo basin, which appears to exhibit changes in flow regime that are a mirror image of those found for the Paraguay at Ladario. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Climate change; Rainfall trends; Runoff trends; Pantanal

1. Introduction

The River Paraguay is a major tributary of the la Plata drainage system (see Fig. 1), the second largest drainage basin (area 3.1 million km^2) in South America and the fifth largest in the world. Of all the tributaries of the la Plata drainage system, the Paraguay is the river which penetrates furthest into the heartland of the South American sub-continent, forming a natural corridor for the development of the region's rich agricultural and mineral resources. There are large deposits of manganese ore that are already exploited; gold and diamond deposits also exist. To the north of the Paraguay basin lies the interfluve separating the la Plata drainage basin from the Amazon system. This region, the Planalto, has seen a dramatic increase since the 1970s in the planting of annual crops, particularly soya and this, together with soil disturbance by cattle in areas still uncultivated,

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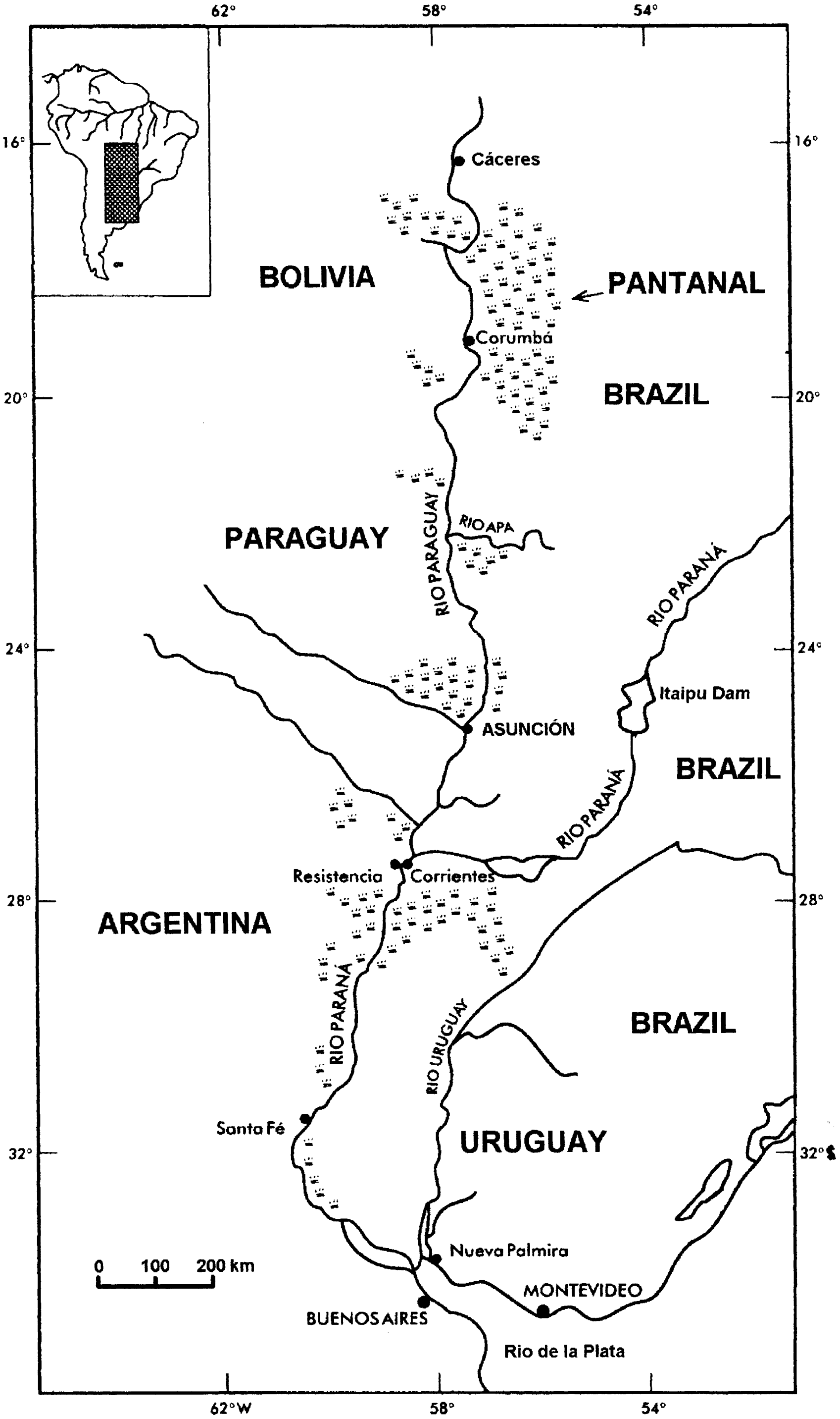

Fig. 1. The la Plata drainage system.

has greatly increased the volume of sediment transported south to the Pantanal and the Paraguay river. To develop the region still further by providing access to the sea, a waterway is planned to run from Argentina to a point upstream of Caceres, a distance of 3600 km. Works are planned that will increase the navigability of the channel through the entire waterway; they include (Tucci and Clarke, 1998): (i) a channel 100 m wide and 3 m deep from Santa Fé in Argentina to Asunción in Paraguay; (ii) a channel 90 m wide and 2.6 m deep from Asunción to Corumbá, in Brazil; and (iii) many works giving at least 1.5–1.8 m of depth for navigation. A major concern is how such changes will affect the Pantanal wetland; the principal questions requiring attention are: (i) will the proposed modifications to the waterway change the wetland hydrology by reducing the volume dispersed over the Paraguay flood plain, and if so, by how much will it be reduced? (ii) what would be the likely effect of a succession of drought years on the flood plain environment?

With respect to the second question, the available rainfall and flow records supply a partial answer, because they include a period of successive years when flow in the Paraguay was much diminished. During this period, there was a heavy investment of capital for cattle production in extensive areas of the Paraguay flood plain, much of which was lost when the hydrological regime changed once again. If the Paraná–Paraguay waterway comes into existence, a major concern — apart from its likely effect on the ecology of the Pantanal — must be that whether it would remain navigable if similar sequences of drought years were to recur in the future. This paper presents some of the results from statistical analysis of the hydrological records, with particular attention to the long-term fluctuations that are clearly evident in this region of great hydrological and economic interest.

2. Description of the basin

The area of the Paraguay basin is $1095 \times 10^3\ \mathrm{km}^2$, representing more than 35% of the la Plata drainage area as a whole, and it drains large parts of four countries: namely Argentina ($165 \times 10^3\ \mathrm{km}^2$), Bolivia ($205 \times 10^3\ \mathrm{km}^2$), Brazil ($370 \times 10^3\ \mathrm{km}^2$) and Paraguay ($355 \times 10^3\ \mathrm{km}^2$). Where the Paraguay joins the River Paraná near Corrientes-Resistencia (see Fig. 1), its mean annual discharge is $2700\ \mathrm{m}^3\ \mathrm{s}^{-1}$, giving a specific discharge of $2.47\ \mathrm{m}^3\ \mathrm{s}^{-1}$ per $1000\ \mathrm{km}^2$; this is far less than the specific discharge of the Paraná, $11.72\ \mathrm{m}^3\ \mathrm{s}^{-1}$ per $1000\ \mathrm{km}^2$. The difference is a consequence both of different rainfall regimes in the two basins, and of the unusually flat topography of the Paraguay basin which includes the Pantanal wetland — itself the world's largest, approximately, $140\ 000\ \mathrm{km}^2$. The distance from Caceres (see Fig. 1) to the sea is 3440 km, whilst the difference between the altitude of Caceres and mean sea level is a few tens of metres. In the Pantanal wetland, slope in the north–south direction is only $0.01\ \mathrm{m\ km}^{-1}$ (Tucci and Clarke, 1998). The difference between the times of flood peaks in the north and south of the Pantanal is about four months, and this has a major influence on the flow regime of the Paraguay, one consequence being that annual peak water-levels can be quite strongly correlated between one year and the next. In essence, the wide extent and low gradients of the Paraguay basin cause it to function as a large evaporation pan. As is well known (Bordas, 1996), the Pantanal has a very distinctive ecosystem that is increasingly under threat from tourism. It has been compared with the Florida Everglades, although the Pantanal is very much larger: even at the start of the 20th century, the area of the Everglades was $10{,}000\ \mathrm{km}^2$, compared with the $140\ 000\ \mathrm{km}^2$ of the Pantanal.

Mean annual rainfall is slightly greater than 2000 mm at the northern boundary of the Paraguay basin, and falls to 800 mm with distance south and west. Maximum rainfall occurs in January in the south of the basin, and in February–March farther north. Within the frontiers of Brazil the Paraguay's major tributaries (Fig. 2) are the Taquari ($51{,}000\ \mathrm{km}^2$) the São Lourenço–Cuiabá ($28{,}000\ \mathrm{km}^2$) and the Miranda–Aquidauana ($5700\ \mathrm{km}^2$). Mean annual flow in the Paraguay tributaries Cuiabá, São Lourenço, Taquari are in the range $300–400\ \mathrm{m}^3\ \mathrm{s}^{-1}$; in the Miranda and Aquidauana about $100\ \mathrm{m}^3\ \mathrm{s}^{-1}$; and in the Itiquira, Correntes, Piquiri and Negro about $50\ \mathrm{m}^3\ \mathrm{s}^{-1}$. Mean flood flows are, respectively, about 1100, 400 and $140\ \mathrm{m}^3\ \mathrm{s}^{-1}$ for the three groups of tributaries (Bordas, 1996).

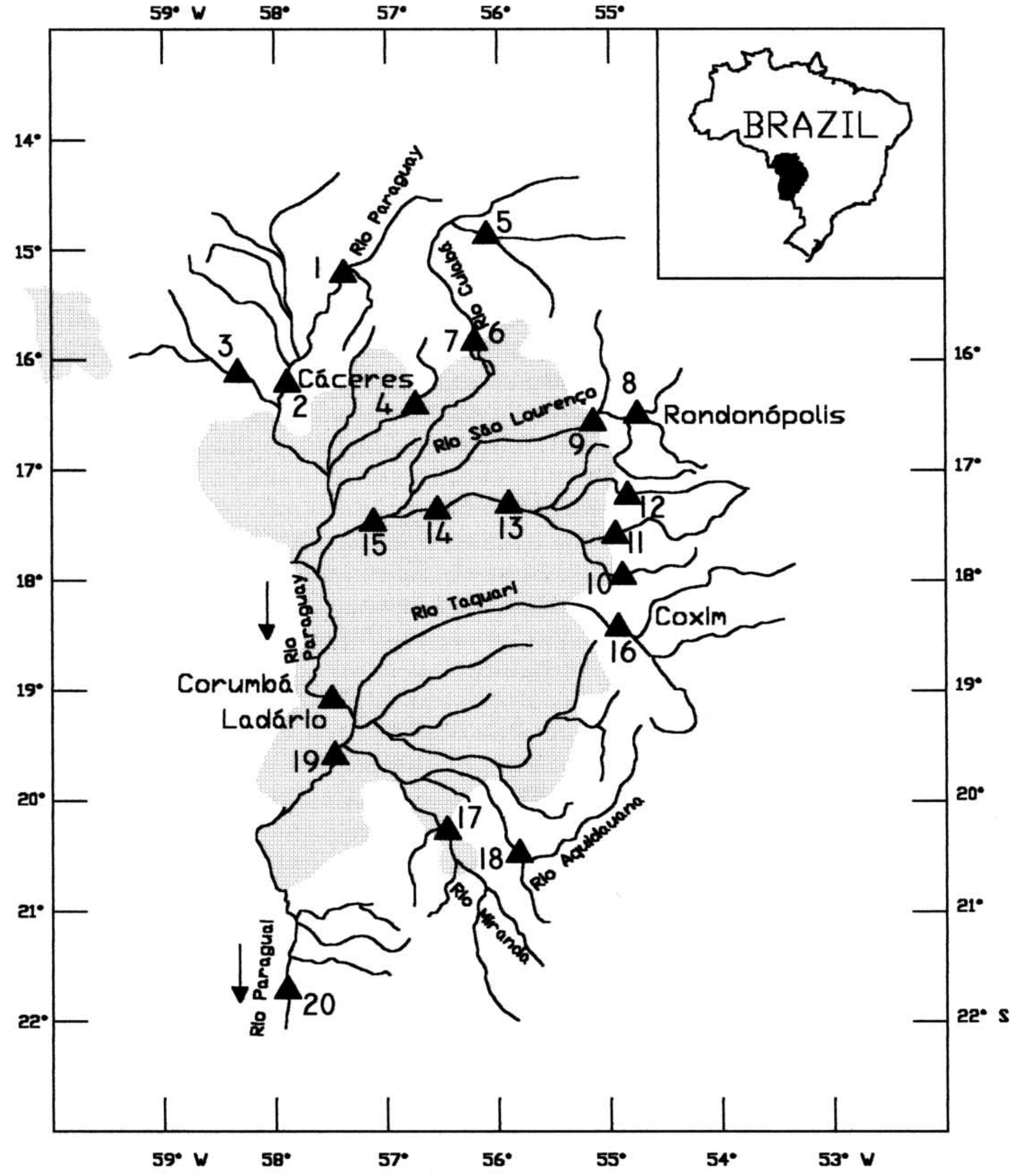

Fig. 2. The River Paraguay and its tributaries. The black triangles show the flow gauging sites listed as numbers 1 to 20 in Table 3.

3. Changes in the long record of water-level at Ladario on the Paraguay

The Brazilian naval post at Ladario is situated towards the downstream limit of the Pantanal (see Fig. 2). Its water-level record is one of the longest in Brazil, starting on 1 January 1900 and extending without loss of data to the present. Because the river channel is very broad and its extent uncertain, no rating curve exists for the Paraguay at Ladario; however, the record of water-level shows much of interest. Fig. 3 shows the annual maximum, annual

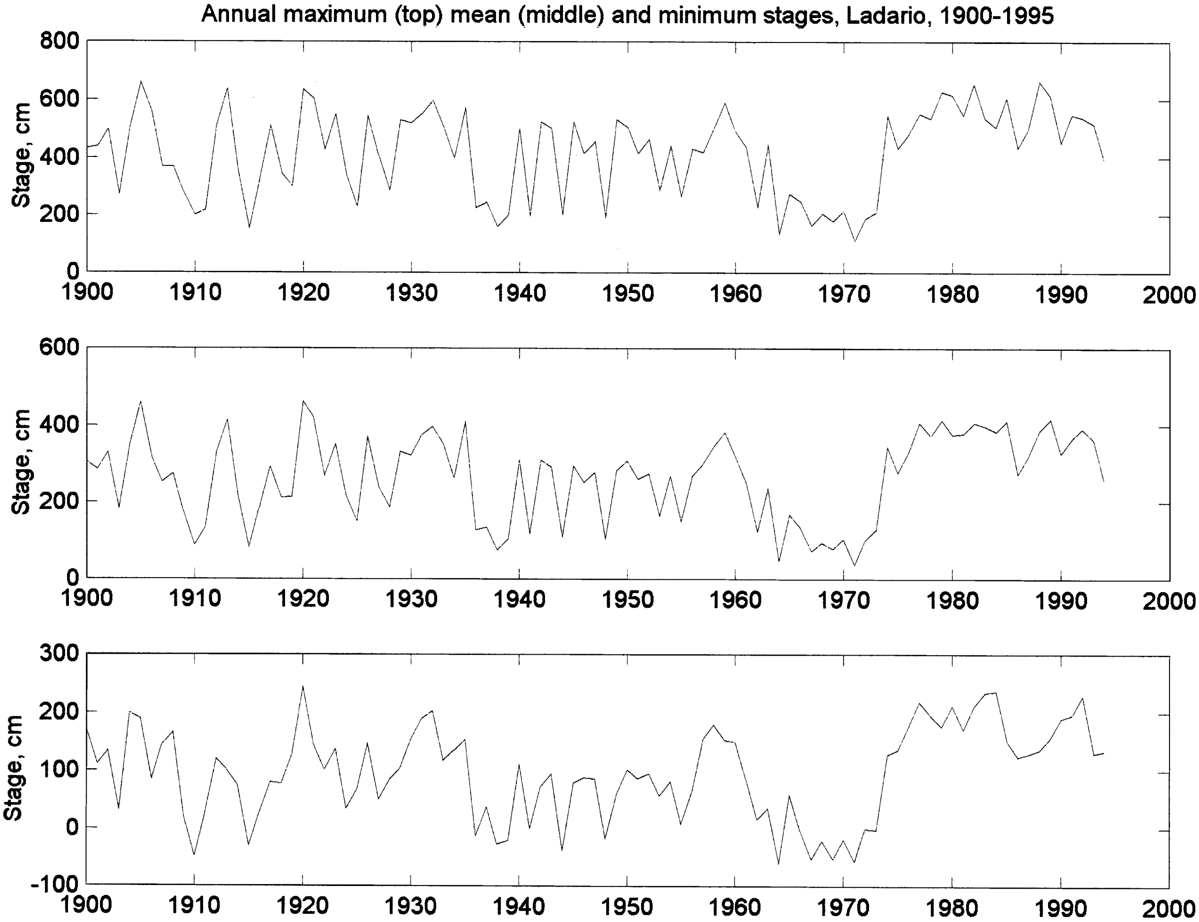

Fig. 3. River Paraguay at Ladario: annual maximum, annual mean, and annual minimum stages for the period 1900–1995.

mean, and annual minimum stages for the period 1900–1995; the remarkable sequence of low water-levels during the decade or so following 1960 stands out clearly, as does the return to higher levels in the period that follows. Inspection suggests that the whole period of record can be divided into three parts: (a) the record up to 1960; (b) the record between 1961 and, say, 1970 inclusive; (c) the period after 1971. Table 1 shows the mean stages, and standard errors of mean stages, for the three periods 1900–1960, 1961–1970, and 1971–1994.

The means presented in Table 1 result from

Table 1
Mean maximum and mean minimum stages (cm), with standard errors of means, for periods 1900–60, 1961–70, and 1971–94: Ladario

	Period		
	1900–60	1961–70	1971–94
Annual maximum	414.1±18.01	280.1±41.04	480.9±30.24
Annual minimum	89.67±8.70	15.40±21.65	143.8±16.28
Difference	324.4±20.0	264.7±46.4	337.1±34.3

Table 2
Serial correlation coefficients up to lag 4 of annual maximum, annual minimum and mean annual stages at Ladario, 1900–94: (a) for sequences as a whole; (b) for sequences up to 1960 only, (c) for period after 1971 inclusive

Whole sequence (±0.102)		Sequence to 1960 (±0.128)		Sequence after 1971 (±0.204)	
lag k	r_k	lag k	r_k	lag k	r_k
Annual maximum stages		1			
	0.416	1	0.139	1	0.639
2	0.293	2	−0.074	2	0.419
3	0.307	3	0.037	3	0.294
4	0.164	4	0.131	4	0.083
Annual minimum stages					
1	0.637	1	0.364	1	0.757
2	0.483	2	0.101	2	0.491
3	0.237	3	0.115	3	0.225
4	0.184	4	−0.060	4	−0.011
Annual mean stage					
1	0.523	1	0.225	1	0.706
2	0.374	2	−0.021	2	0.468
3	0.338	3	0.037	3	0.272
4	0.199	4	−0.110	4	0.096

inspection of the data plotted in Fig. 3, so it is inappropriate to make formal significance tests of differences. However, it seems fairly clear that: (a) mean annual maxima, and mean annual minima, are far less during the period 1961–1970, than for either of the periods 1900–1960 or 1971–1994; (b) there is no strong evidence of real difference between mean maximum stages 1900–1960 and 1971–1994 (the difference between these means is 66.8 ± 35.2 cm); (c) there is some evidence that the mean annual minimum stage for 1971–1994 was greater than the mean annual minimum stage for 1900–1960, the difference being 54.13 ± 18.46 cm (143.8–89.67).

The period from 1960 onwards exerts a strong influence on the apparent correlational structure of the maximum and minimum annual stage sequences, as Table 2 shows. This correlation stems from the large storage within the basin contributing to a carry-over effect from one year to the next. Table 2 shows that, when each sequence is taken as a whole, there is a strong year-to-year correlation that is greater for annual minimum stages than for annual peak stages, the significance of the correlation extending up to the third year (as assessed by comparison with their approximate standard errors $\pm 1/\sqrt{N}$, shown in the table). However, for the period up to 1960 (61 years) there is no evidence of year-to-year correlation between annual peak stages, and the correlation between annual minima in consecutive years, while still significant, is much reduced. For the period from 1971 onwards (25 years), however, both annual maximum and annual minimum stages are strongly serially correlated, with evidence of carry-over effects persisting up to the second year; the strong serial correlation is also evident in Fig. 3. It is clear that a considerable perturbation in the hydrological regime occurred about 1960 and persisted for a period of some years. The intervening 10-year period 1961–1970 is too short for reliable conclusions to be drawn about between-year correlation.

4. Trends in flow records from other stations on the River Paraguay

Despite its length and completeness, the Ladario record gives limited information on the hydrological regime of the River Paraguay because of the absence of stage–discharge relation for the site (that is, a curve, or table, from which discharge can be calculated from water-level or 'stage' measurements). Shorter records of discharge, sometimes with missing

Table 3
Station numbers, codes, river, gauge location and period of record for sites in the Paraguay basin with flow records: see Fig. 2

Number	Code	River	Gauging site	Period of record
1	66010000	Paraguay	Barra do Bugres	1965–84
2	66070004	Paraguay	Caceres	1974–
3	66076000	Jaurú	Baia Grande	1966–83
4	66110000	Bento Gomes	Poconé	1969–83
5	66231000	Manso	Fazenda Raizama	1961–83
6	66260001	Cuiabá	Cuiabá	1961–92
7	66260002	Cuiabá	Varzea Grande	1969–83
8	66450001	Vermelho	Rondonópolis	1965–93
9	66460000	São Lourenço	Correntes	1969–84
10	66480000	Piquirí	BR163	1969–83
11	66490000	Correntes	BR163	1969–83
12	66525000	Itiquira	BR163	1969–83
13	66600000	Piquirí	S. Jerônimo	1969–84
14	66650000	Piquirí	S. José do Piquirí	1969–84
15	66750000	Cuiabá	Porto Alegre	1967–84
16	66870000	Taquarí	Coxím	1966–84
17	66910000	Miranda	Miranda	1965–83
18	66945000	Aquidauana	Aquidauana	1968–83
19	66960008	Paraguay	Porto Esperança	1964–84
20	67100000	Paraguay	Porto Murtinho	1965–84

sections, are available for the sites listed in Table 3 and plotted in Fig. 2, for which stage–discharge relations do exist. To facilitate comparison between flows at all 20 sites, mean annual flows were standardised by subtracting the annual mean flow over the available full years of record, and dividing by their standard deviation. All flows were thereby converted to a unit-free scale, with mean zero and variance one. Figs. 4–7 show plots of the standardised flows from the 20 stations in Table 3, in groups of five; for each group of five stations, the plotting symbols are in the order triangle, square, star, circle, inverted triangle for the five stations for which station codes are given. All four sets of five stations show negative values of standardised flow for a period up to about 1972, after which it increased to strongly positive values in the years that followed. The pattern is most clearly defined for the downstream stations in the Paraguay basin, on the River São Lourenço and southwards (Figs. 5–7), and is least clearly defined for the stations shown in Fig. 4 for which data sequences are more patchy.

Thus it can be concluded that flow data from the 20 stations shown in Table 3, although incomplete for some years and despite the limited period of record, confirm the picture shown by the much longer stage records at Ladario. Galdino et al. (1997), reporting on the apparent hydrological changes in the River Taquari, one of the Paraguay's tributaries draining the Pantanal, described the onset of a dry period in about 1960–1961 which terminated in 1972–1973; Müller et al. (1998) reported a similar result for the Paraná basin lying within Brazil; and the present paper extends the result of Galdino et al. (1997) to the Paraguay basin as a whole. Thus the spatial extent of the change in the flow regime following 1972 seems to have been very considerable.

5. Evidence of change in rainfall records

If the reality of the change in the Paraguay basin flow regime during the (approximate) period 1960–1970 is accepted, it is natural to seek an explanation in the rainfall records. Fig. 8 shows locations of 36 rain gauge sites, 15 within the Paraguay basin, for which records were analysed for existence of time trends; gauges lying outside the Paraguay basin itself were included to get an idea of the spatial extent of any changes in rainfall regime if such changes were detected. Some of the records are long, but analysis is complicated by the fact that several (for some sites,

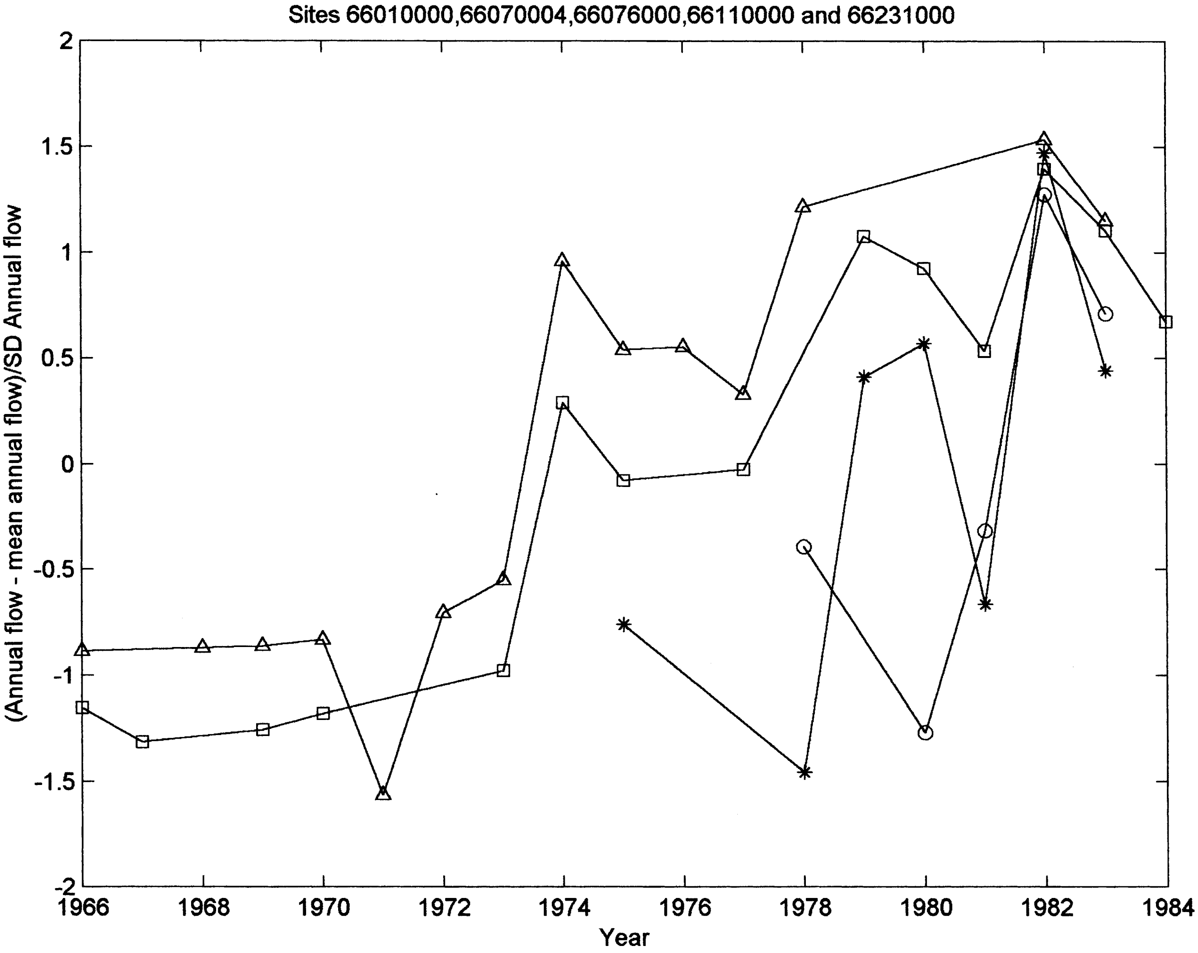

Fig. 4. Standardised mean annual flows (standardised by subtraction of their mean, and division by their standard deviation) for river gauges 66010000 (triangles apex up), 66070004 (squares), 66076000 (stars), 66110000 (circles) and 66231000 (inverted triangles). For names and localities of gauge sites, see Table 3 and Fig. 2.

many) years are incomplete or missing. To illustrate, Fig. 9 shows plots of the complete years of record for eight of the 36 gauges at higher latitudes, where records tend to be more complete; two of these gauges (those at 17° S 53° W and 17° S 54° W) had sufficient data to warrant the more detailed analysis discussed below. Both in Fig. 9 and in subsequent analyses, annual totals were standardised to have zero mean and unit variance.

Because the area covered is so large, relatively small changes in rainfall regime could result in substantial changes to the flow regime. To simplify the picture, therefore, annual rainfall at each of the 36 sites was converted to a Bernoulli variable, having the value zero or one according to whether the standardised rainfall (having zero mean, unit variance) was positive or negative: that is, above average, or below average. Bernoulli variables are widely used as indicators of presence or absence of particular characteristics (e.g. Hosmer and Lemeshow, 1989) and have also been extensively used in rainfall studies (e.g. Coe and Stern, 1982; Stern and Coe, 1984). Then, for each of the years between 1960 and 1996 inclusive, two quantities r and N were obtained: N being the number (maximum 36) of sites for which the rainfall record in that year was complete, and r the

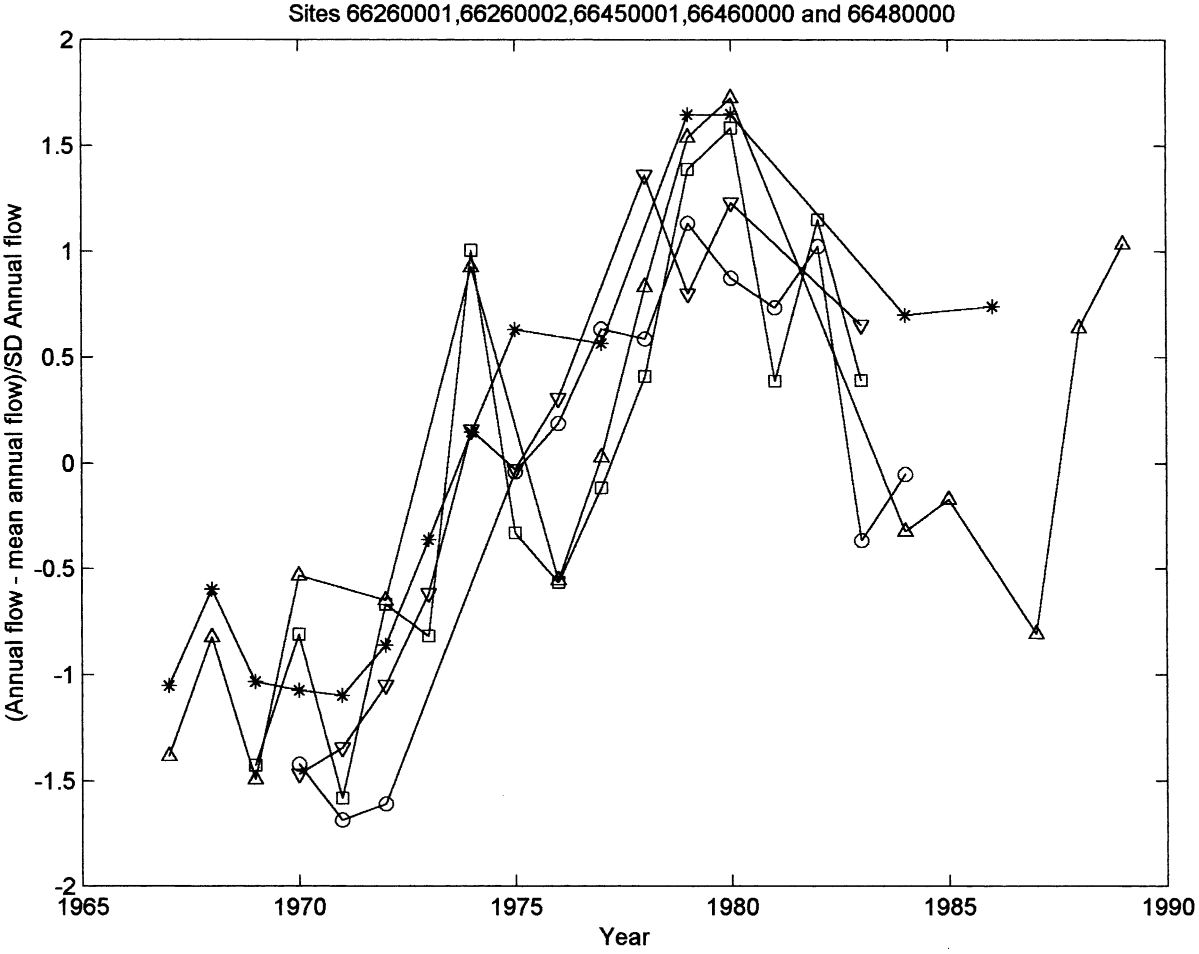

Fig. 5. As for Fig. 4: river gauges 66260001, 6626002, 66450001, 66460000 and 66480000. Symbols follow the same sequence as in Fig. 4.

number of sites (out of N) for which the standardised rainfall was positive (and therefore above average, in relative terms). If no trend in rainfall existed, the proportion $p = r/N$ would be expected to vary randomly about some constant value over the period 1960–1996; however, if a trend were present, this proportion $p = r/N$ would be expected to increase over the period. To test the hypothesis that no trend existed in the standardised annual rainfalls at the 36 sites, a logistic regression of the form $\ln\{p_t/(1 - p_t)\} = \beta_0 + \beta_1 t + \beta_2 t^2 + \epsilon_t$ was fitted by iteratively weighted least squares, and the coefficients β_1 and β_2 were tested for departure from zero. Both coefficients were highly significant, and estimated as $\hat{\beta}_1 = 0.1211 \pm 0.0315$ and $\hat{\beta}_2 = -0.002434 \pm 0.000799$.

Fig. 10 shows the observed frequencies (left-hand figure) r/N, and observed proportions (right-hand figure), together with those calculated from the fitted logistic regression; despite considerable variation in the number N of gauges with complete records in any given year, the high proportions of sites with below-average rainfall (low r/N) in the period 1960–1972 stands out clearly, as does the increase in r/N in the years that followed. The rainfall pattern shown by Fig. 10, therefore, follows the pattern of annual flows described earlier and presented in Figs. 4–7, suggesting that the trend in standardised mean annual flow is at least partially explained by changes in standardised mean annual rainfall. It is necessary to point out, however, that this logistic regression analysis takes

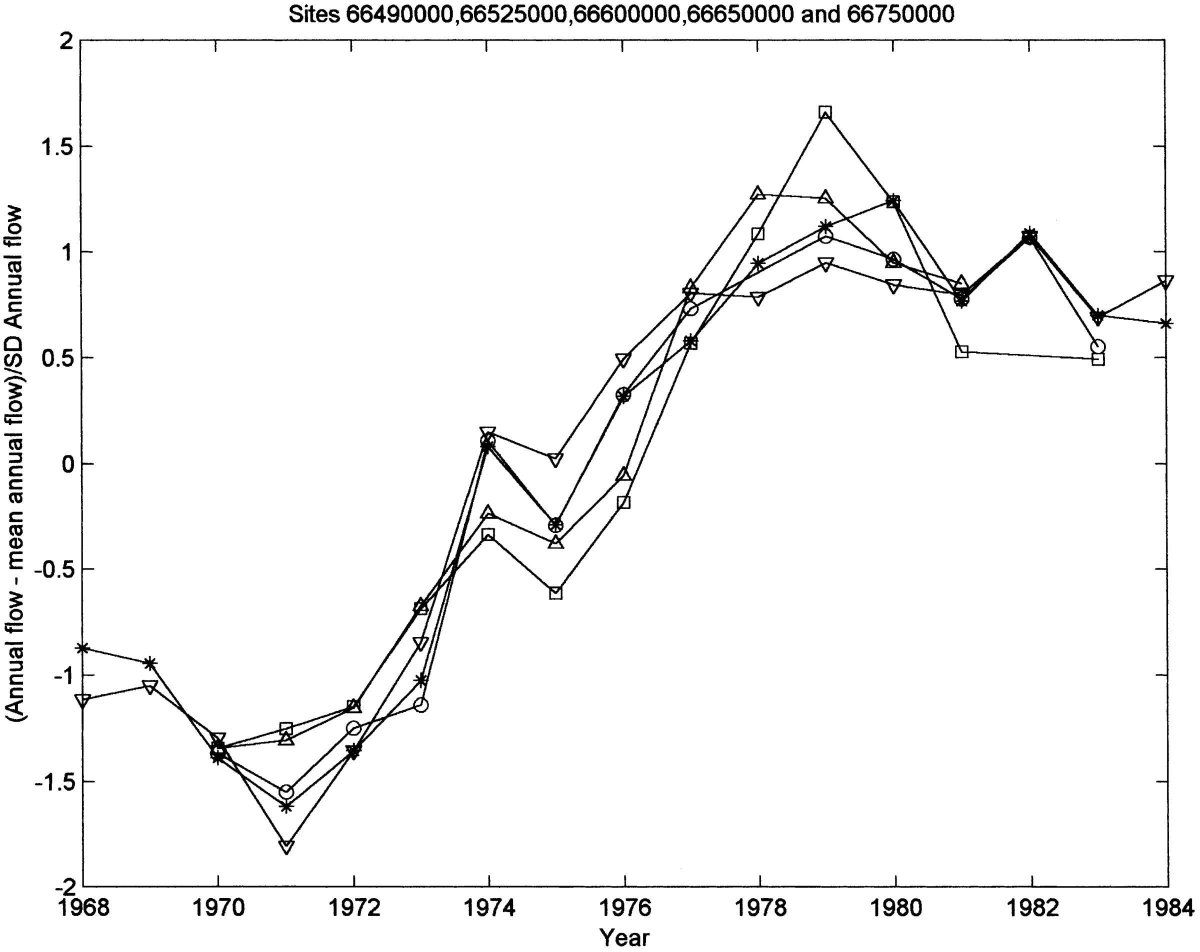

Fig. 6. As for Fig. 4: river gauges 66490000, 66525000, 66600000, 66650000 and 66750000. Symbols follow the same sequence as in Fig. 4.

no account of any spatial dependence in the Bernoulli (0–1) variables; this is probably not unreasonable in this region where much of the rainfall results from convection processes.

Because the 36 rain-gauge sites are distributed over a wide area, the question arises: is there evidence that the pattern in annual rainfall, described in the preceding paragraph, varied spatially over the region as a whole? To seek an answer to this question, the 36 sites were divided into groups of six, according to their latitude bands; the first group consisted of the six gauges nearest the equator, the next group consisting of the six gauges lying in more southernly latitudes, the final group consisting of the six gauges in latitudes farthest from the equator. The analysis described in the preceding paragraph was then repeated for the gauges in each latitude band. Since the denominator N in the proportion r/N is now six or less, the binomial proportions have lower precision and no very clear picture emerges. Table 4 shows the estimated values of the coefficients β_1 and β_2 of the logistic regressions fitted for the six groups of gauges; positive signs for β_1 are found in five of the six groups, although their departures from zero (linear trend absent) are significant in only two of the six groups. However, reference to Fig. 8 giving the locations of the 36 gauges, and to Fig. 2 showing the basin of the Paraguay, confirms that the group of gauges (the fifth group in the sequence) where the trend was most marked lay between latitudes 16 and 18°

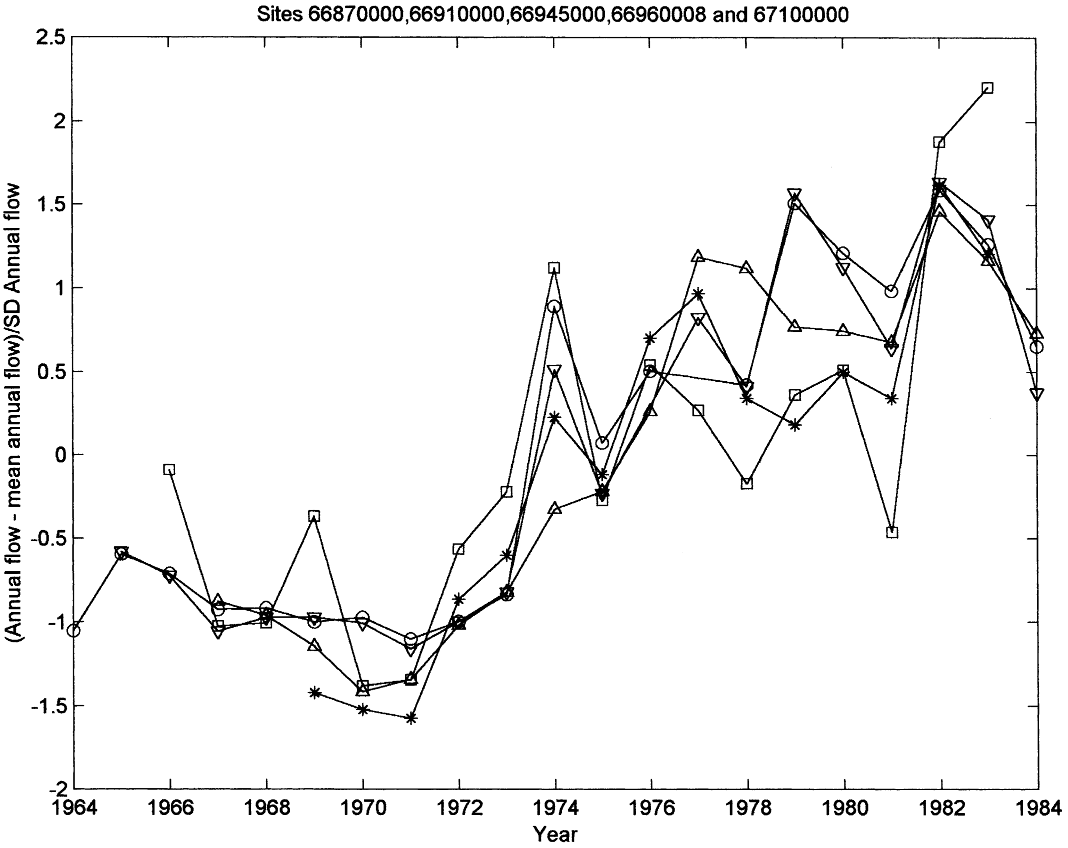

Fig. 7. As for Fig. 4: river gauges 66870000, 66910000, 66945000, 66960008 and 67100000. Symbols follow the same sequence as in Fig. 4.

S, within the more northerly part of the Pantanal. These gauges are sited in land draining to the River Paraguay near Caceres, and to the rivers Cuiabá and São Lourenço.

6. Changes in the pattern of daily rainfall sequences

The preceding section discussed trends in annual rainfall totals at the 36 sites, and evidence was presented showing that the decade of low discharge in the River Paraguay corresponded to a period of lower-than-average regional rainfall. This section seeks to elucidate further the nature of the change in rainfall pattern between the decade 1960–1970 and the period following. A change in rainfall regime might take effect through a combination of factors, so that a period in which annual rainfall is increased may arise because rainfall is more frequent, and/or because rainfall is of higher intensity. To determine whether such factors operate, it is necessary to analyse sequences of daily rainfall.

Two gauges from group 5 of Table 4 were selected because this group showed significant evidence of changing rainfall pattern, and because the records for these two gauges were the most complete of the six. The two gauges both lay at approximately latitude 17° S, at longitudes 53 and 54° W, respectively — that is between the towns of Coxím and Rondonópolis on the map in Fig. 2. The gauge at 17° S 53° W had 10 years' record in the period 1960–1970 and 15 in the subsequent period; the gauge at 17° S 54° W had 9 and 17, respectively. For each gauge and for each period,

Fig. 8. Locations of 36 rain gauge sites, lying within the Paraguay basin and neighbouring basins, whose records were used to explore time trends.

the record of daily rainfall was analysed in two ways. The first analysis considered the probability, for each day of the year, that a dry day on this date would be succeeded by another dry day; thus for each day t ($t = 1, 2, 3, \ldots, 365$), the proportion r_t/N_t was calculated, where N_t is the number of years for which day t was dry, and r_t is the number of years out of the N_t for which day $t + 1$ was also dry. Since, for a seasonal rainfall regime, the proportion would be expected to show periodic behaviour, the proportions r_t/N_t were used to fit a logistic regression of the form

$$\ln\{p_t/(1 - p_t)\} = \beta_0 + \beta_1 \cos(2\pi t)$$

$$+ \beta_2 \sin(2\pi t) + \ldots$$

and from the fitted regressions, estimates of the probability — for each day of the year — that a dry day would be followed by another were obtained.

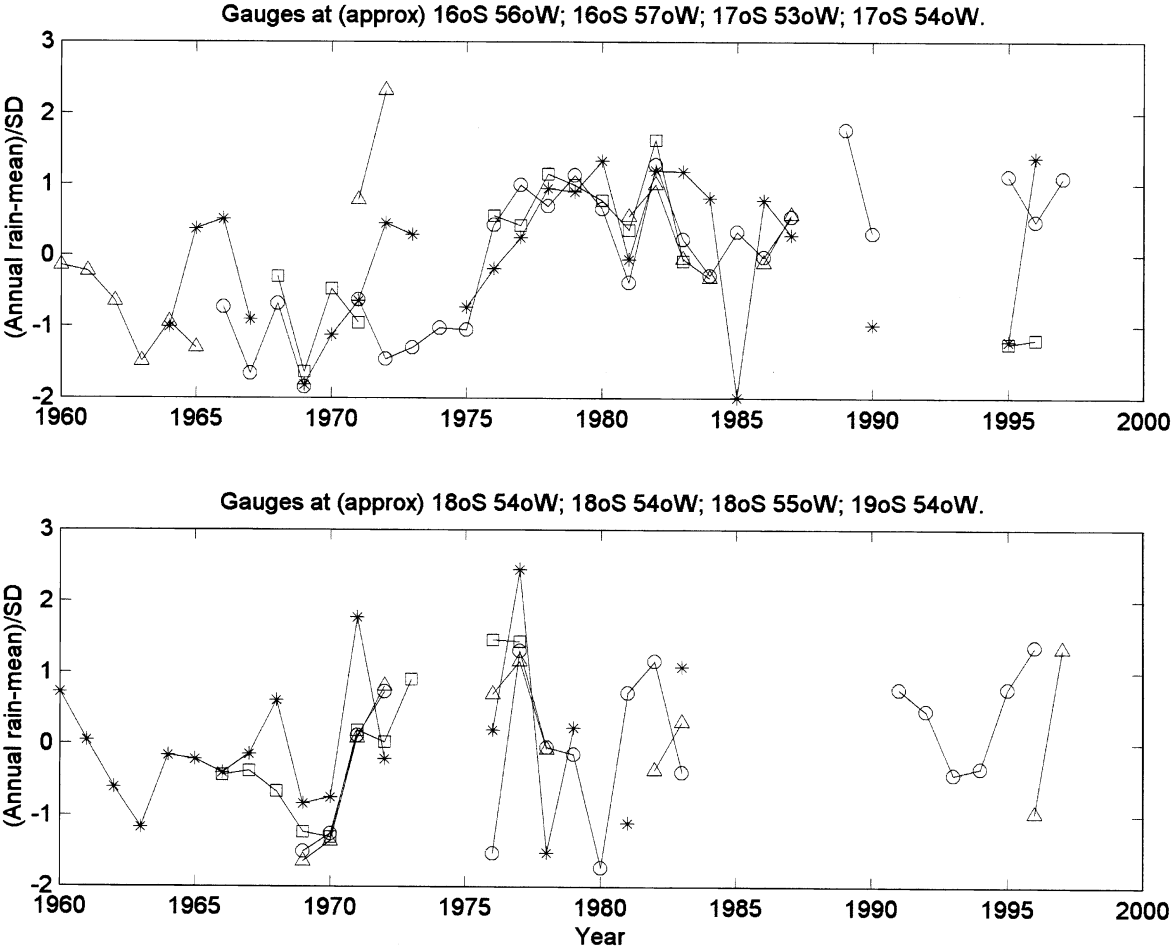

Fig. 9. Standardised mean annual rainfall: upper figure, gauges 16° S 56° W,16° S 57° W, 17° S 53° W, 17° S 54° W (upper); gauges 18° S 54° W, 18° S 54° W, 18° S 55° W and 19° S 54° W (lower).Symbols for the gauges follow the sequence, triangle, square, star, circle.

The second analysis was concerned with rainfall amounts. For each day of the year, the number of years in which rain fell on that day, and the depths of rain that fell, were calculated; the depths were transformed to logs, and the mean of the logged values was regressed (using a weighted regression to allow for varying numbers of rain-days) upon harmonic terms cos($2\pi t$), sin($2\pi t$), cos($4\pi t$), sin($4\pi t$)... From these regressions, fitted values of the mean log(daily rainfall) were obtained for each of the two periods, for comparison.

Figs. 11 and 12 show results obtained from the two gauges at about 17° S 53° W, and 17° S 54° W, respectively. The upper figure of each pair shows the curves fitted by logistic regression to the proportions of dry days that were also followed by dry days; the full line shows the curve fitted for the critical period from 1960–1970 (where records permitted), and the broken line shows curve fitted for the period after 1970. For both gauges, the curve 1960–1970 lies above that for post-1970; the interpretation is that for both gauges, dry spells tended to be more persistent in the critical period than in the period following 1970. The curves in the lower half of each figure show the curves fitted to the means of log-transformed rainfall, on days when rain fell. Here, the curve for the critical period 1960–1970 lies generally below the curve for the period post-1970 for the gauge at 17° S 53° W, and

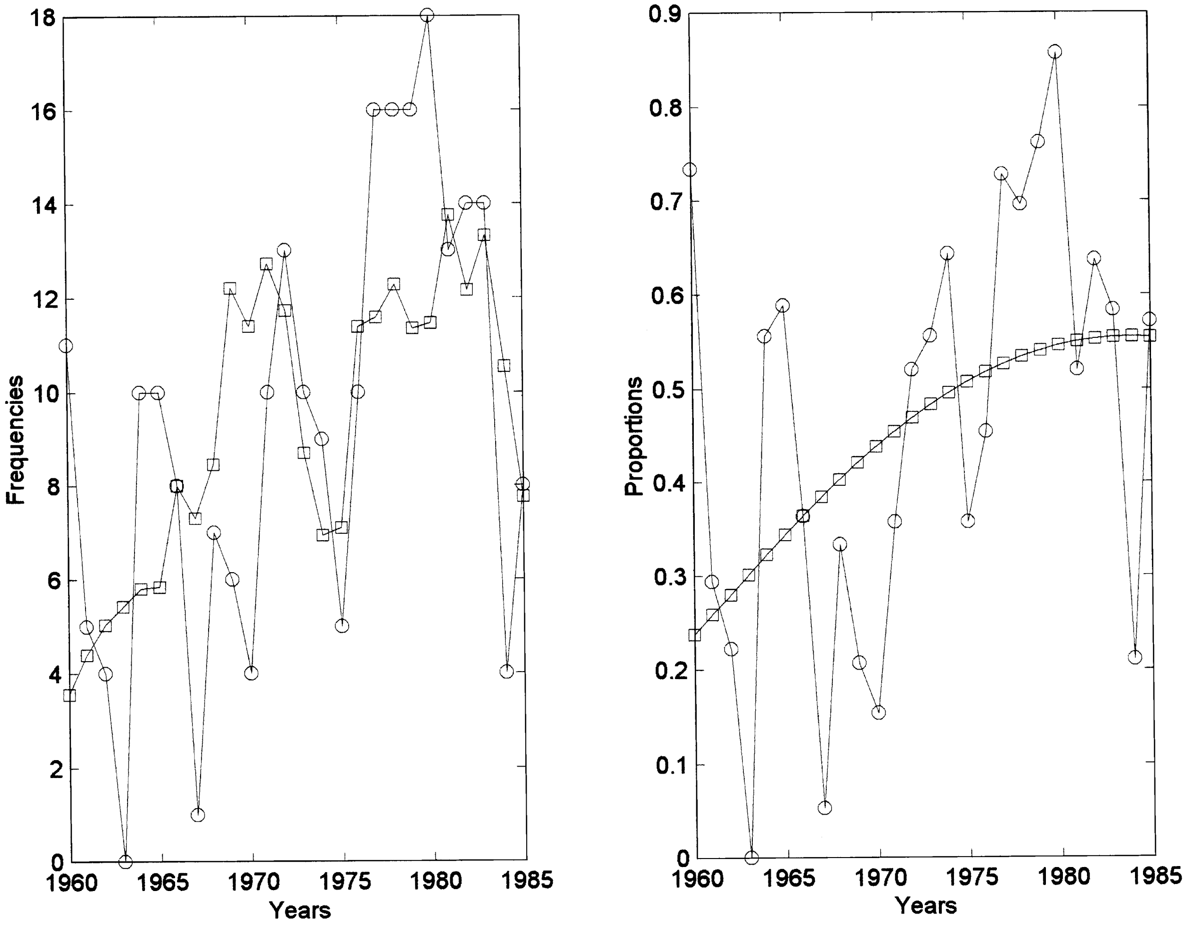

Fig. 10. Left-hand figure: observed frequencies of above-average rainfall (frequencies *r* out of *N* sites), calculated from the logistic regression $\ln\{p_t/(1-p_t)\} = \beta_0 + \beta_1 t + \beta_2 t^2 + \epsilon_t$ described in the text. Observed frequencies are circles, expected frequencies denoted by squares. Right-hand figure: observed proportions *r*/*N* (circles), compared with fitted values (squares).

totally below it for the gauge at 17° S 54° W. The interpretation is that on days when it rained, less rain fell, on average, on wet days during the critical period 1960–1970, than in the period post-1970.

Recalling that the two gauges analysed are those with fullest records in the group of six gauges in the latitude band where the trend in standardised rainfall was most significant, it is seen that, during the period 1960–1970, dry spells were more persistent at both gauges, and on wet days less rain fell on average, than in the period following 1970. Thus for the period 1960–1970 there is some evidence of differences in the temporal pattern of daily rainfall, and in the amounts of rain that fell, between latitudes 16 and 18° S, in the northern half of the Pantanal. Differences between the two periods: (i) 1960–1970, (ii) after 1970, are also evident from the monthly and annual totals for the two gauges over these periods, as shown in Table 5.

7. Discussion

The analyses described above illustrate the spatial extent of the changes in the hydrological regime, for both rainfall and runoff, over the Paraguay drainage basin. To the extent that spatial changes in patterns of runoff (water-level, in the case of Ladario) have been

Table 4
Estimates of coefficients β_1 and β_2 of the logistic regressions fitted for the six groups of six gauges

Group of gauges	β_1	β_2
1	0.1352±0.0949	−0.00202±0.00306
2	0.2054±0.0970*	−0.00429±0.00216
3	−0.0082±0.0757	0.00073±0.00222
4	0.1248±0.0782	−0.00281±0.00194
5	0.4270±0.1200**	−0.00835±0.00268**
6	0.0840±0.0758	−0.00131±0.00194

* Significance at 5% level.
** Significance at 1% level.

demonstrated, the results given above complement those of Genta et al. (1998) who showed trends not only for the Paraguay record at Puerto Banejo (27° 20′S, 58° 30′W), but also for three other rivers in south-eastern South America: namely the Uruguay, Paraná and Negro (in the country Uruguay). For all four rivers, Genta et al. (1998) discerned an increasing trend in runoff, by calculating a thirty-year running mean; however, such a long-period mean masks the abruptness of the change that apparently occurred round about 1960, and again about 10 years later. Genta et al. (1998) also used a non-parametric (Wilcoxon) test to compare median flows for the two periods: (i) up to 1940, and (ii) after 1970, on the basis that 'there is no definite evidence that annual streamflows cannot be considered independent of each other'; the serial correlations shown in Table 2 of this paper, although calculated using river stage and not the sequence of discharge data, may suggest otherwise.

Insofar as the above results attempt to explain changes in runoff (or water-level) in terms of rainfall and its spatial distribution, they complement the findings both of Genta et al. (1998) and Amarasekera et al. (1997), whose analysis was restricted to runoff. Care is needed, however, where the analysis of long-term hydrological records is restricted exclusively to runoff, because of the complicating effects of land-use change: it is well-known (e.g. Bruijnzeel, 1996; Sahin and Hall, 1996) that deforestation invariably leads to increased flow in rivers (although runoff decreases again if there is re-growth (Erskine, 2000)), and natural forest cover has diminished in many parts of the South American interior over the last 30 years as cattle-rearing and intensive production of annual crops — particularly soya — followed forest clearance. Indeed, it is possible that part of the flow increase since 1970 (see Figs. 4–7) is a consequence of deforestation.

Because of the high spatial variability of rainfall in tropical regions, it is more difficult to reveal time trends in rainfall than in runoff, and the patchiness and gaps in records from rain gauges in the Paraguay basin complicates any analysis still further. However, the results from our rainfall analysis appear to support those of Müller et al. (1998) who made an extensive analysis of both flow and rainfall records from the Paraná basin (lying to the east of the Paraguay) above the Itaipú hydropower installation, currently still the world's largest; this plant was designed using Paraná flow records up to 1970. By means of very careful statistical analysis, Müller et al. (1998) showed that mean flows at 26 stations on the Paraná and its tributaries increased, after 1970, by between 8% (River Paranaiba) and 45% (River Paranapanema). The increases in flow increased with distance downstream. In their analysis of over 40 rainfall records from the Paraná basin, they too found evidence of increased rainfall at all sites after 1970, associated with increased frequency of rainfall events. The mean annual increases ranged from 8 to 17%.

Both in terms of rainfall and river runoff, therefore, our results support other hydrological and climate studies of the South American sub-continent. But there are other, wider, relationships that invite further study. Laraque et al. (1997) and Orange et al. (1997) analysed runoff records from River Congo at Brazzaville, and from its tributary the Oubangui at Bangui; the former record began in 1902 and the latter in 1936. For the Congo at Brazzaville, Laraque et al. (1997) defined three distinct periods: (i) from the

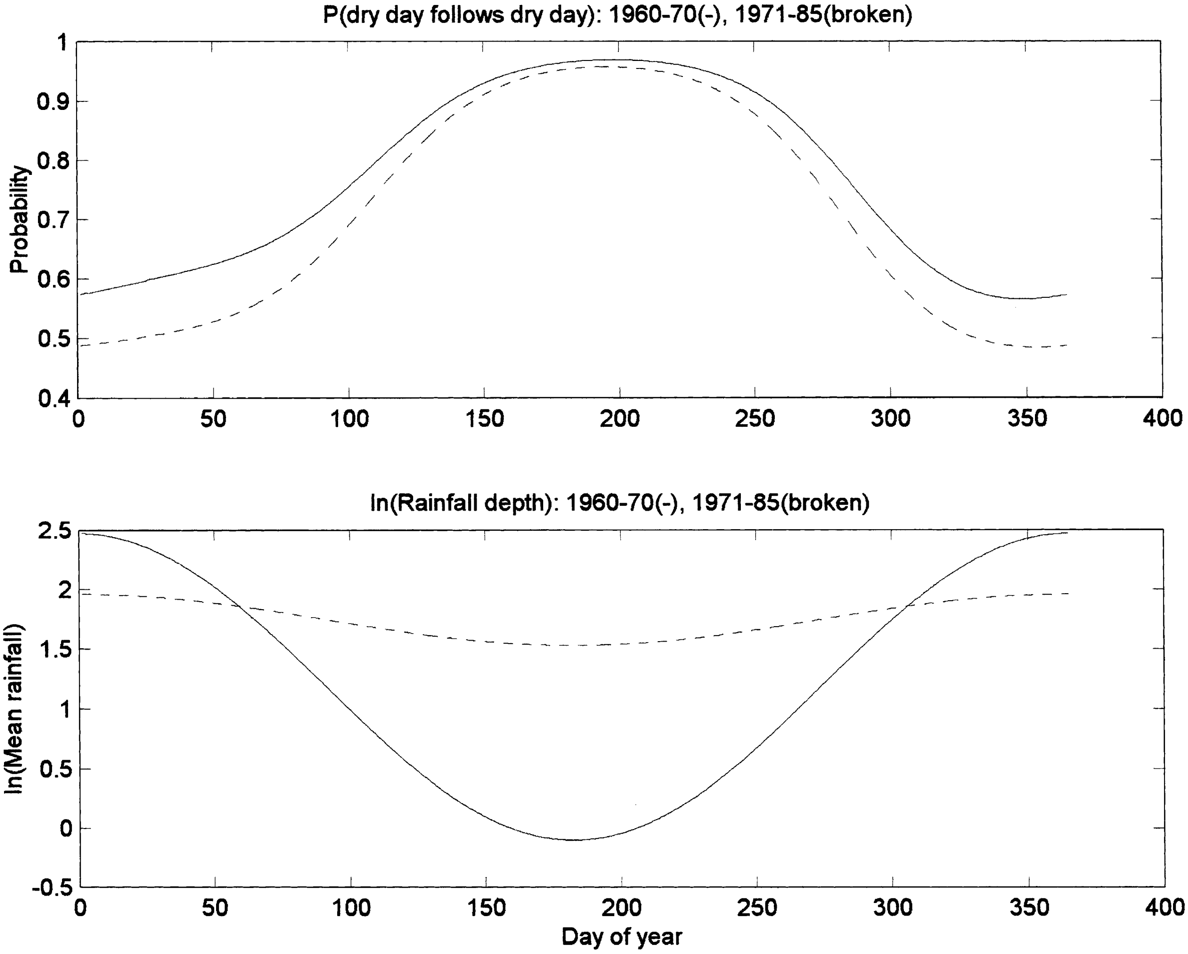

Fig. 11. Plots refer to gauge sited at approximately 17° S 53° W (upper figure). For each day 1–365, plot of probability that a dry day is followed by another dry day. Full line obtained from data in period 1960–70, broken line for 1971–85 (lower figure). For days when rain fell, plot shows mean log rainfall, for days 1 through 365. Full line: period 1960–70; broken line: period 1971–85.

record beginning in1902 up to 1960, when annual mean discharge was stable; (ii) a period from 1960 to 1970, which they described as wet period, and which included the annual flood with a 100-year return period; (iii) the period from 1971 onwards, marked by decreasing runoff, the severity of which has increased since 1982. This pattern is the mirror image of the pattern found in the Paraguay basin. A pattern similar to the Congo at Brazzaville was also found for the Oubangui at Bangui (Orange et al. 1997): a stable period up to 1960, a wet period between 1960 and 1970, and a period of decreasing flow from 1971 onwards: the exact opposite of the River Paraguay behaviour. Other Congo tributaries, also analysed by Laraque et al. (1997) confirmed the pattern. However, patterns in Congo basin rainfall were much less distinct, possibly because of the same difficulties as those encountered in the analysis of Paraguay basin rainfall: namely, incomplete and patchy records in a tropical region where rainfall distribution is spatially very variable. Nevertheless, Laraque et al. (1997) were able to conclude that over the Congo basin as a whole, mean annual rainfall in the period 1970–1989 was 4.5% less than that during the period 1951–1969.

Thus, at least in terms of flow regimes, the Congo is

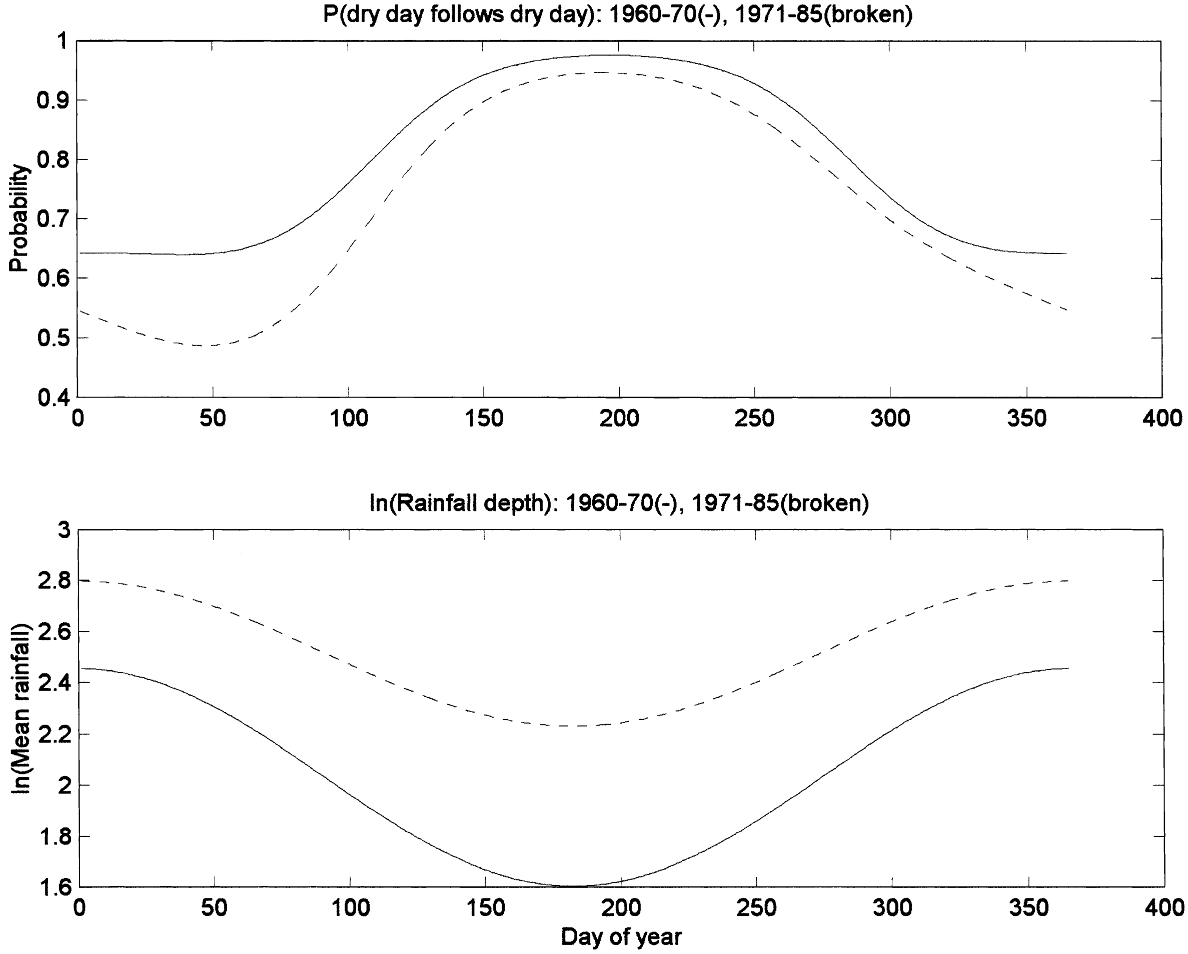

Fig. 12. Plots refer to gauge sited at, approximately, 17° S 54° W. Explanation of upper and lower figures as for Fig. 11.

the mirror opposite of the Paraguay and other rivers of the la Plata drainage basin. In fact the hydrological fluctuations in the Congo region appear to have extended to an even larger region, including the Sahel and the Gulf of Guinea. Le Barbé and Lebel (1997) show that as the decade of the 1960s gave way to the 1970s, there was an abrupt change in mean rainfall over the Sahel, with a persistent drought beginning around 1970 and reductions in mean rainfall of between 7 and 42% between periods 1950–1967 and 1968–1989. Farther south, the Gulf of Guinea also showed quite abrupt changes in rainfall (Servat et al., 1997; Paturel et al., 1997); the 1960s were slightly wetter than the 1950s, whilst the 1970s and 1980s experienced a long and persistent drought.

Some exploration (Kousky et al., 1984; Molion and Moraes, 1987; Damázio et al., 1997) of the physical processes involved has begun, but to our knowledge, studies are still at a rudimentary level and much more work is needed to clarify how atmosphere and ocean interact in the southern hemisphere where the proportion of land to ocean is much less than in the northern hemisphere. Genta et al. (1998) showed that the 30-year running means of the four rivers Paraná, Paraguay, Negro and Uruguay, and the 30-year running mean of the (extended) mean sea-surface temperature (SST) anomalies in the central and eastern equatorial Pacific (averaged over the three regions 6°–2° N, 170°–190° W; 2° N–6° S, 180°–90° W; and 6°–10° S, 150°–110° W), have increased together

Table 5
Monthly mean rainfalls, and annual means, for two periods: gauges at 17° S 53° W, and 17° S 54° W

	Gauge 17° S 53° W		Gauge 17° S 54° W	
	Period			
	1960–70 (10 years)	1971–85 (15 years)	1960–70 (9 years)	1971–87 (17 years)
Jan	241.3	290.1	193.0	319.6
Feb	239.7	208.6	221.6	293.8
Mar	172.0	219.8	165.7	237.9
Apr	109.2	113.9	88.5	153.4
May	69.3	52.2	27.7	86.6
Jun	7.0	24.8	9.3	38.2
Jul	18.9	8.3	12.6	12.6
Aug	9.5	26.9	15.0	32.7
Sep	48.9	96.0	43.4	105.5
Oct	193.5	133.6	123.1	119.3
Nov	249.1	239.4	178.1	211.2
Dec	189.9	310.4	161.7	280.8
Totals	1548.2	1724.0	1239.5	1891.6

during the period after 1960. No correlation was given, presumably because the correlation between the two series of 30-year running means would greatly over-estimate the true correlation between the annual series. Amarasekera et al. (1997), however, do quote correlations between annual discharge from the River Paraná at two gauging sites (Posadas, Corrientes) and SST anomalies, with the latter averaged over three-monthly periods. Eight such three-monthly periods were used beginning in March–April–May of the year preceding the year for which mean annual discharge was calculated, and ending with September–October–November of the year for which mean annual discharge was calculated. At both Posadas and Corrientes, correlations of about 0.4 were found between mean annual discharge and mean SST anomaly for the period December–January–February (December of the previous year, January and February of the current year). Intuitively, however, it is difficult to see how a causative relation could exist between a three-month SST mean anomaly and mean discharge over entire years.

Although the Paraguay basin lies within the larger basin of the River Paraná, and it has been reported that flow in the Paraná is correlated with ENSO events (Amarasekera et al., 1997), the ENSO influence in the Upper Paraguay itself appears to be much smaller (Ropelewski and Halpert, 1987; Grimm et al., 1998a). Within South America, ENSO influence on rainfall is most marked in the south-east, north, north-east, and Pacific coast of the sub-continent. In the south-east, the correlation between rainfall and ENSO events is positive, rainfall tending to be above average in Uruguay, eastern Argentina and particularly in southern Brazil (Ropelewski and Halpert, 1987; Diaz et al., 1998; Grimm et al., 2000; Grimm et al., 1998b). Flow in the region's principal rivers is also positively correlated with ENSO events (Mechoso and Perez Iribarren, 1992; Amarasekera et al. 1997). However, in the north and north-east of South America, the correlation with ENSO events is negative: during El Niño events, rainfall tends to be below average. This correlation has been detected over a wide region and reported by various authors including Ropelewski and Halpert (1987) and Souza et al. (2000). Flows in the Rivers Amazonas in Brazil and Magdalena in Colombia show the same tendency (Molion and Moraes, 1987; Amarasekera et al., 1997; Restrepo and Kjerfve, 2000). Ropelewski and Halpert (1996) show that the negative correlation between rainfall and ENSO, found in the north of South America, decreases with distance south, and that the positive correlation between rainfall and ENSO in the south-east of South America decreases with distance north, suggesting a transition zone between latitudes 10° S and 25° S for which ENSO influence is less marked. It is within this transition region that the Upper Paraguay lies. The findings reported by Ropelewski and Halpert (1996) have been confirmed subsequently by others: thus Souza et al. (2000) confirms that the negative correlation between rainfall and ENSO found in northern South America diminishes with distance south, whilst Grimm et al. (2000) confirms that the positive correlation rainfall–ENSO found in the south-east of the sub-continent diminishes with distance north. For the Upper Paraguay region, we are aware of only one study of rainfall–ENSO correlation (Grimm et al., 1998a), and this showed that for the centre-west of Brazil, in which the Upper Paraguay lies, there is very little evidence of such correlation. This appears to confirm that the Upper Paraguay basin lies within the transition zone, with more southerly regions showing (positive) rainfall–ENSO correlations typical of the south of Brazil, and more northerly regions showing (negative) correlations typical of Amazonia.

The physical causes of rainfall and runoff variation in the Paraguay basin need further study. Robertson and Mechoso (1998) reported a strong cyclical component in flows in both the rivers Paraná and the Paraguay with a period of 10 years, concluding that this cycle had no correlation with ENSO, although it correlated well with SSTs in the tropical North Atlantic. It is interesting to note that the Paraguay basin, the Sahel and the Congo basin all show persistent changes in rainfall and/or runoff, even though no correlation with ENSO has been found in any of these regions. On the other hand, regions showing good correlation with ENSO, such as the south of Brazil and Uruguay (Robertson and Mechoso, 1998), show much greater within-year variability and smaller year-to-year variation. Another feature common to all three regions is their large gradients in rainfall; in the Sahel, mean annual rainfall increases from north to south at about 1 mm km^{-1} (Le Barbé and Lebel, 1997), whilst south of the Sahel (Paturel et al., 1997) and in the Congo basin gradients in mean annual rainfall are also considerable: for example in the basin of the River Oubangui, one of the main tributaries of the Congo, the rainfall gradient is about 2 mm km^{-1} (Orange et al., 1997). In the River Paraguay basin, annual rainfall increases from about 800 mm in the west of the basin to almost 2000 mm in the north-east, over a distance slightly more than 500 km, a gradient also of about 2 mm km^{-1}. As noted by Le Barbé and Lebel (1997) for the Sahel, persistent changes in rainfall over such large areas correspond to movements of several hundred kilometres in mean annual isohyets.

Clearly, research is needed to establish the causative mechanism by which annual flows in the Paraguay and other basins in the la Plata drainage system, are related to ocean–atmosphere interactions. There may be no alternative to empirical, correlational studies until such time as global climate models are perfected in terms of both their physical description and their spatial resolution.

8. Conclusions

Analysis of flow measured at 20 sites, rainfall measured at 36 sites, and a 95-year record of water-level at one site in the basin of the River Paraguay (area 1095×10^3 km^2) showed the following.

The flow regime during the approximate period 1960–70 — perhaps extending to 1972 — differed substantially from the flow regime both before and after. The long record of Ladario water-levels suggested that the changes between one period and the next were considerably abrupt, and that the periods differed not only in terms of mean water-levels but also in terms of the year-to-year correlational structure within the record.

Despite the fragmentary nature of the 36 rainfall records, an explanation for the increased flows since 1970 was found in the increases of rainfall, as assessed in terms of the frequency of annual rainfalls greater than the long-term mean rainfall.

There was some degree of consistency in the change of rainfall pattern across the Paraguay basin as a whole. A detailed examination of daily rainfall characteristics in records from two gauges showed that during the 1960–70 period, when river flows were low, dry spells were more persistent and, on days when rain did fall, the amounts of rain were generally smaller.

The results obtained were compared with results obtained by other researchers using flow records from the Rivers Paraguay, Paraná, Negro and

Uruguay in the la Plata basin. The results were also compared with findings of persistent rainfall and discharge changes in Africa, especially from the Congo basin, which appears to exhibit changes in flow regime that are virtually the exact opposite of those found for the Paraguay. The observed changes of rainfall and discharge over the Paraguay river basin bear little relation to ENSO events, and other explanations for the changes must be sought.

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