INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **22**: 1663–1686 (2002)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/joc.815

INTERANNUAL RAINFALL VARIABILITY IN THE AMAZON BASIN AND SEA-SURFACE TEMPERATURES IN THE EQUATORIAL PACIFIC AND THE TROPICAL ATLANTIC OCEANS

JOSYANE RONCHAIL,[a,*] GÉRARD COCHONNEAU,[a] MICHEL MOLINIER,[a] JEAN-LOUP GUYOT,[a] ADRIANA GORETTI DE MIRANDA CHAVES,[b] VALDEMAR GUIMARÃES[c] and EURIDES DE OLIVEIRA[c]

[a] *IRD, CP 7091, Lago Sul 71619-970, Brasilia (DF), Brasil*
[b] *ANEEL, SGAN 603, ed. DNC, 70830-030 Brasilia (DF), Brasil*
[c] *ANA, SPF, Area 5, qd 3, bl B, Brasilia (DF), Brasil*

Received 20 June 2001
Revised 17 June 2002
Accepted 17 June 2002

ABSTRACT

Rainfall variability in the Amazon basin is studied in relation to sea-surface temperatures (SSTs) in the equatorial Pacific and the northern and southern tropical Atlantic during the 1977–99 period, using the HiBAm original rainfall data set and complementary cluster and composite analyses.

The northeastern part of the basin, north of 5 °S and east of 60 °W, is significantly related with tropical SSTs: a rainier wet season is observed when the equatorial Pacific and the northern (southern) tropical Atlantic are anomalously cold (warm). A shorter and drier wet season is observed during El Niño events and negative rainfall anomalies are also significantly associated with a warm northern Atlantic in the austral autumn and a cold southern Atlantic in the spring. The northeastern Amazon rainfall anomalies are closely related with El Niño–southern oscillation during the whole year, whereas the relationships with the tropical Atlantic SST anomalies are mainly observed during the autumn. A time–space continuity is observed between El Niño-related rainfall anomalies in the northeastern Amazon, those in the northern Amazon and south-eastern Amazon, and those in northern South America and in the Nordeste of Brazil.

A reinforcement of certain rainfall anomalies is observed when specific oceanic events combine. For instance, when El Niño and cold SSTs in the southern Atlantic are associated, very strong negative anomalies are observed in the whole northern Amazon basin. Nonetheless, the comparison of the cluster and the composite analyses results shows that the rainfall anomalies in the northeastern Amazon are not always associated with tropical SST anomalies.

In the southern and western Amazon, significant tropical SST-related rainfall anomalies are very few and spatially variable. The precipitation origins differ from those of the northeastern Amazon: land temperature variability, extratropical perturbations and moisture advection are important rainfall factors, as well as SSTs. This could partially explain why: (a) the above-mentioned signals weaken or disappear, with the exception of the relative dryness that is observed at the peak of an El Niño event and during the dry season when northern Atlantic SSTs are warmer than usual; (b) rainfall anomalies tend to resemble those of southeastern South America, noticeably at the beginning and the end of El Niño and La Niña events; (c) some strong excesses of rain are not associated with any SST anomalies and merit further investigation. Copyright © 2002 Royal Meteorological Society.

KEY WORDS: rainfall variability; Amazon basin; SST tropical Atlantic; ENSO; composite analysis; cluster analysis

1. INTRODUCTION

The Hydrology and Geodynamics in the Amazon basin (HiBAm) project[1] aims to document and forecast the variability of surface hydrology and sediment transport through the Amazon basin. As discharge variability is mainly explained by rainfall variability (e.g. see Molinier *et al.*, 1996), this paper focuses on the relationship

* Correspondence to: Josyane Ronchail, IRD, CP 7091, Lago Sul 71619-970, Brasilia (DF)-Brasil; e-mail: josyaneronchail@yahoo.fr

between rainfall and sea-surface temperatures (SSTs) in the equatorial Pacific (PAC) and in the tropical North (NATL) and South (SATL) Atlantic.

Observations and results from models show that the SSTs over the tropical Atlantic influence the interannual variability of climate in South America, particularly in the northeast region of Brazil (Nordeste) (Hastenrath and Heller, 1977; Moura and Shukla, 1981; Harzallah *et al*., 1996; Nobre and Shukla, 1996) and over the eastern Amazon (Molion, 1987, 1993; Marengo, 1992; Nobre and Shukla, 1996; Roucou, 1997).

The influence of PAC SSTs on Nordeste and Amazon rainfall, as well as the Pacific–Atlantic relationships and the local conditions that provide rainfall anomalies, have been described in various papers (Hastenrath and Heller, 1977; Kousky *et al*., 1984; Rao and Hada, 1987; Aceituno, 1988; Rogers, 1988; Marengo, 1992; Marengo and Hastenrath, 1993; Moron *et al*., 1995; Nobre and Shukla, 1996; Enfield and Mayer, 1997; Roucou, 1997; Marengo *et al*., 1998; Uvo *et al*., 1998; Liebmann and Marengo, 2001; Pezzi and Cavalcanti, 2001; Molinier *et al*., in press).

With the exception of Marengo (1992), Liebmann and Marengo (2001), and Molinier *et al*. (in press), little attention has been paid to the relationship between tropical SSTs and rainfall variability over the entire Amazon basin. The relative influences of El Niño–southern oscillation (ENSO) and of the tropical Atlantic SSTs on the Amazon basin rainfall are not well known yet. We propose a new analysis of the space–time variability of rainfall in relation to the tropical SSTs using the original rainfall data set of the HiBAm project.

In Section 2 we describe the data sets used in this work and the time–space rainfall distribution in the Amazon basin. In Section 3 we analyse the relationship between rainfall and SSTs in the tropical oceanic basins. We synthesise the results and offer some possible explanations for their occurrence in Section 4.

2. RAINFALL AND SST DATA SETS

2.1. Rainfall data set and rainfall distribution in the Amazon basin

Monthly rainfall data were provided by the Agência Nacional de Energia Eléctrica (ANEEL), as well as by the National Meteorological Services of Brazil (INMET), Bolivia (SENAMHI), and Ecuador (INAMHI).

The data set has been controlled and homogenized by the 'regional vector method' (Hiez, 1977; Hiez *et al*., 1992), which models the rainfall observation in a region in the form of relevant indexes of the monthly rainfall and coefficients related to each rain gauge. 879 out of approximately 1400 rain gauges located in the Amazon basin or in the vicinity were selected by the method and clustered into 50 homogeneous regions. The method was also used to correct monthly rainfall and to fill gaps in the rainfall information. The method was not applied in the Andean areas because the rain gauge density was too low to represent the high spatial variability of the rainfall in these regions. For the 248 rain gauges finally selected for this study, 4.75% of the monthly data were obtained by filling in gaps and 3.92% were obtained from corrected data. The percentage of monthly missing data is 7%.

In the Brazilian Amazon basin, many of the rain gauge stations were installed in the mid 1970s, after the development of the Trans-Amazonian roads and population settlements (e.g. along the Porto-Velho–Cuiba axis in Rondonia and along the Rio Branco on the Manaus–Venezuela axis). A quarter of the 248 stations selected have data that begin between 1977 and 1980. That is one of the reasons for selecting the 1977–99 period for the present study. Another reason is that the 1970s was an important period of time for oceanic changes with the warming (cooling) of the southern (northern) Atlantic beginning in the early 1970s (Roucou, 1997) and the warming of the tropical Pacific beginning in 1976. In addition, Ronchail (1997) showed that a rupture appears at the beginning of the 1970s in the rainfall of the Amazonian lowlands of Bolivia, with negative anomalies during the 1950s and 1960s and positive anomalies during the 1970s and 1980s. Thus, when observing these data sets on a decadal time scale, the 1977–99 period appears almost homogeneous.

The spatial distribution of the stations is not random (Figure 1) but is organized along rivers and roads. We choose to use observed data rather than mean gridded data because the redundancy of stations in some places is a way of verifying information robustness and because lack of data in other places is also a limitation.

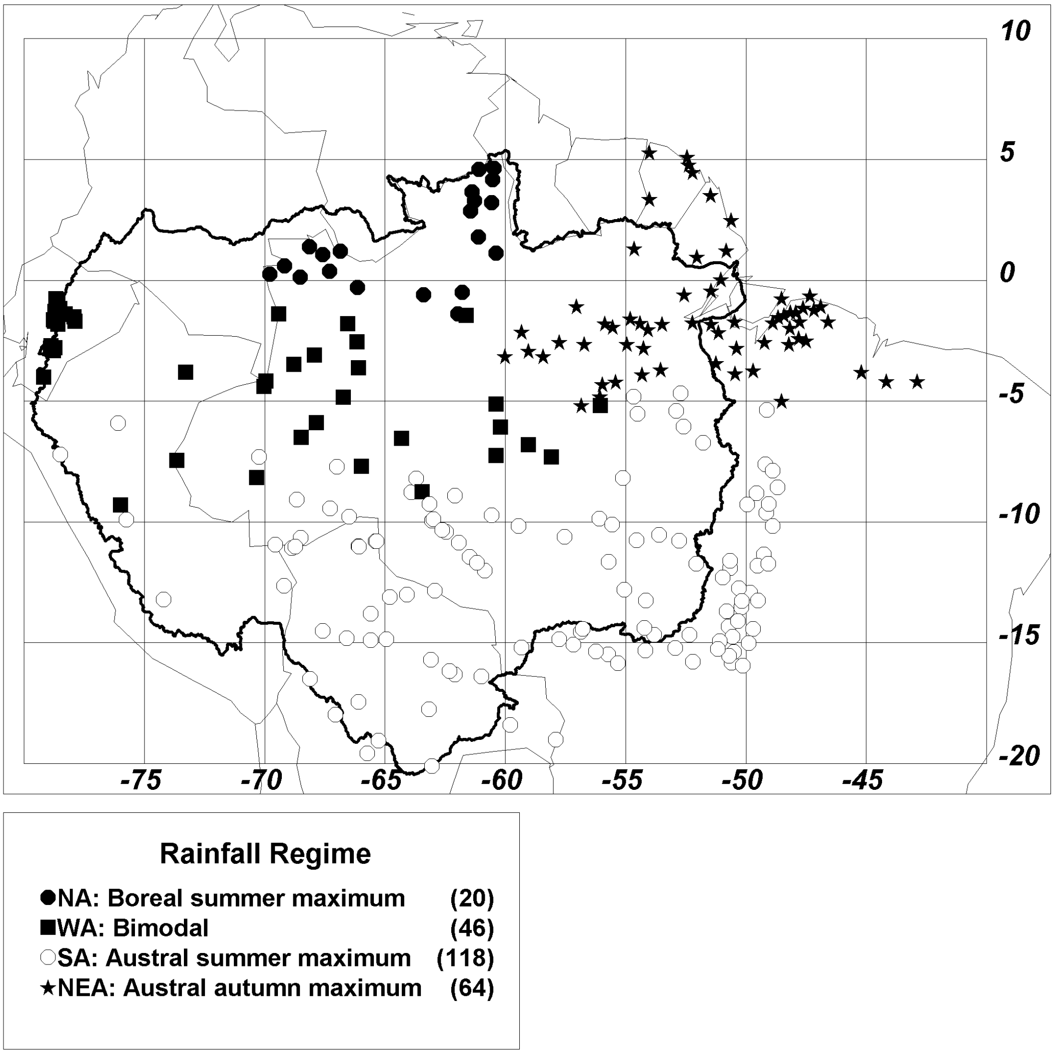


Figure 1. Location of the rain gauges and of the main Amazonian regions characterized by their rainfall regimes (see text)

Annual rainfall in the Amazon basin is generally above 2000 mm around the equator. There are two regions having a maximum above 3000 mm, one on the Atlantic coast and the other over the northwestern Amazon. Annual rainfall decreases from the equatorial regions towards the tropics and the Nordeste (under 1500 mm) and in the inner Andean valleys (under 1000 mm). Higher rainfall variability is generally associated with lower rainfall totals; however, variability is high in the northwestern Amazon along the upper Rio Negro valley.

In order to take into account the different rainfall regimes in the Amazon basin, we computed an agglomerative hierarchical cluster analysis on the 12-monthly 1977–99 rainfall means. We used Ward's method. Cluster membership is assessed by calculating the total sum of squared deviations from the mean of a cluster. The criterion for fusion is that it should produce the smallest possible increase in the error sum of squares (Wilks, 1995; Fielding, 2002).

Four regions were identified (Figure 1) whose rainy and dry seasons are consistent with those defined by Kousky (1988), Horel *et al*. (1989), and Figueroa and Nobre (1990):

- The northern Amazon (NA) region, where a rainfall maximum is registered from April to August, which corresponds to a Northern Hemisphere position of the maximum of convection. There is no real dry season, as this region is very close to the equator. Figure 2(a) shows the small percentage of annual rainfall (less than 10%) received in December–February (DJF), and Figure 2(c) shows the large value (nearly 50%) of June–August (JJA) rainfall, particularly along the Rio Branco.

- The western Amazon (WA) region, where the maximum rainfall occurs from January to May, when the continental maximum of convection migrates towards the south. However, no real dry period is registered and a bimodal equatorial regime is often identified. The percentage of rain does not vary much from one quarter to another (Figure 2(a)–(d)).
- The southern Amazon (SA) region, where the rainy season is from October to April, December and January, corresponding to the southernmost position of the maximum of convection in South America. Figure 2(a) shows that DJF receives nearly 50% of the annual rain, whereas JJA is dry (Figure 2(c)); however, in the southwestern basin the winter rainfall can reach 5 to 15% of the annual amount, and the percentage remains under 5% in the southeast. Advection of cold air along the Andes and associated fronts (De Oliveira and Nobre, 1986; Ronchail, 1989; Seluchi and Marengo, 2000) are responsible for this unusual winter percentage.

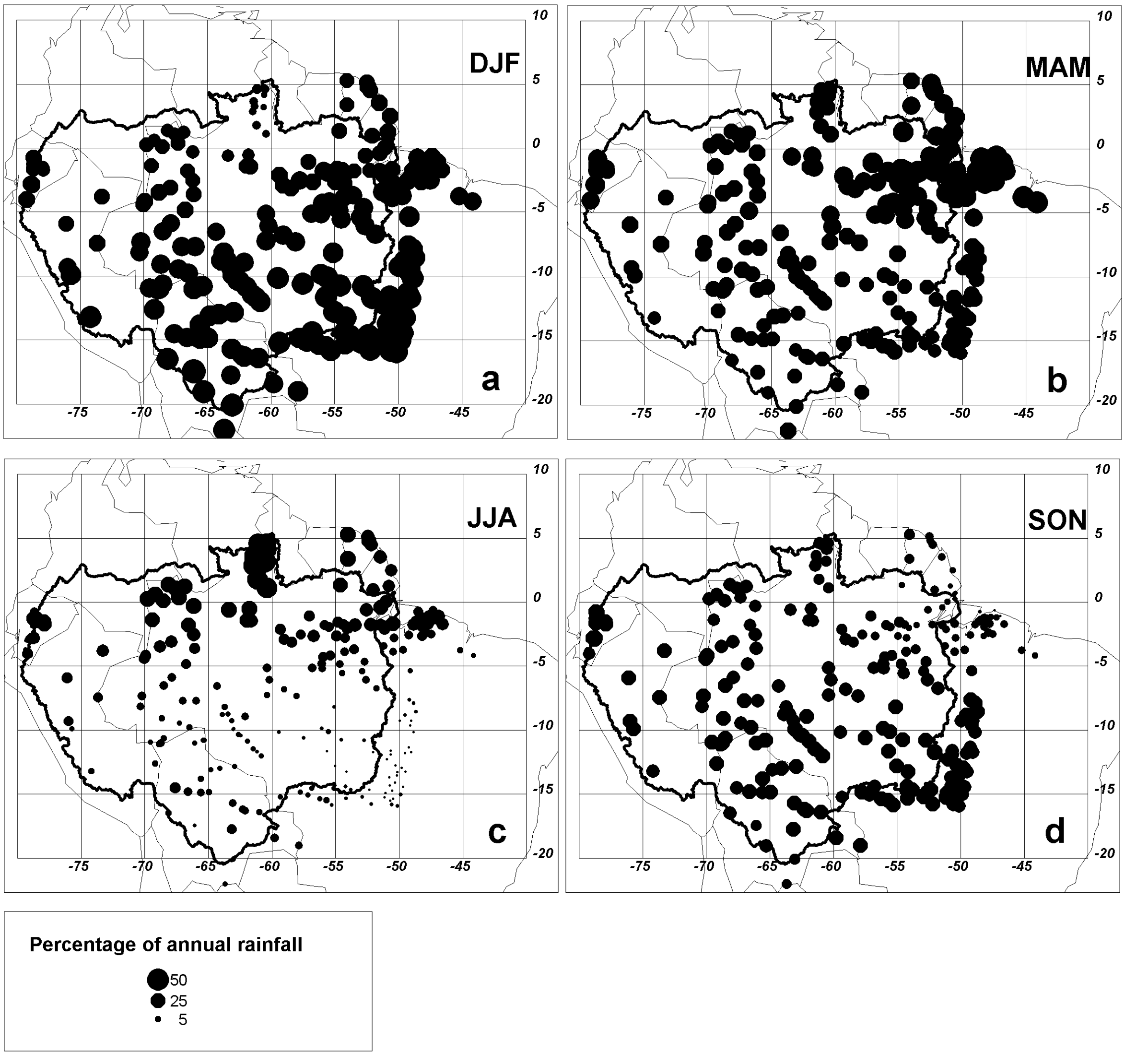


Figure 2. Percentage of annual rainfall during (a) DJF, (b) MAM, (c) JJA, (d) SON

- The northeastern Amazon (NEA) region, including the area extending from the mouth of the Amazon until Manaus, with its rainy season from December to May when the maximum of convection migrates towards the north (Figure 2(a) and (b)).

As a new cycle begins in September, with the beginning of a rainy or rainier season in the Southern Hemisphere, the period from September to August has been chosen as the hydrological year. As each season is associated with a peculiar feature in one or more regions, we shall use rainfall data integrated over 3-month periods (DJF, March–May (MAM), JJA, and September–November (SON)).

2.2. SST data

The SST data set is from the Climatic Prevision Centre of the National Oceanic and Atmospheric Administration (CPC-NOAA). Monthly SSTs (1950–2000) are provided for Niño3 (5 °S–5 °N, 150–90 °W) in the equatorial Pacific Ocean, the NATL (5–20 °N, 60–30 °W) and the SATL (0–20 °S, 30 °W–10 °E) (Figure 3(a)–(c)). The southern Atlantic and the Pacific SSTs have a similar annual cycle, which is out of phase with the cycle of the northern Atlantic SSTs. Maximum and minimum temperatures occur at the end of the respective summer and winter seasons. The southern Atlantic is the coldest oceanic basin and has a large and regular annual amplitude (Figure 3(a)). The PAC SST has the strongest interannual variability (Figure 3(c)).

SST anomalies computed over the 1977–99 period (standardized values) are used to define anomalous years and quarters in the oceanic basins; they appear in Table I. Cold and warm years and quarters in the tropical Atlantic and in the Pacific (Niño3 block is used) are those with SST anomalies exceeding three-quarters of the standard deviation. El Niño and La Niña events are consistent with those described by Trenberth (1997).

On an interannual time scale, the SATL SST anomalies are inversely correlated with the Niño3 SSTs (Figure 4). The correlation between both series is −0.47; it is significant at the 0.05 level. NATL SST and Niño3 SST anomalies are not correlated. In the Atlantic Ocean, opposite anomalies of the northern and southern basin SSTs can be observed, as in 1980–81, 1983–84, and 1984–85; but the same-sign anomalies are often simultaneous in both Atlantic basins during the 1977–99 period, as in 1987–88 and 1992–93. This results in no correlation between SST anomalies in the northern and the southern tropical Atlantic oceans (Figure 4). Therefore, even though a dipolar oscillation has been proposed in the tropical Atlantic, little evidence for a coherent signal appears in this work, on an interannual time scale, as has been shown by Houghton and Tourre (1992) and Enfield and Mayer (1997). For these reasons, NATL and SATL SST anomalies will be treated separately.

3. TIME–SPACE ASSOCIATIONS BETWEEN RAINFALL AND SST ANOMALIES

These associations are analysed using two different approaches.

First, starting with the rainfall anomalies (standardized values), we describe their main spatial patterns in the Amazon basin using a cluster analysis, and we compute the SST anomalies corresponding to the different classes of rainfall anomalies. This approach has the advantage of taking into account all the years of the period studied, which includes many different kinds of rainfall anomaly structures. However, only a rough idea is given of the rainfall–SST relationships, as patterns of precipitation anomalies could probably be associated with factors other than SSTs.

Secondly, starting with the SST anomalies, we compute the rainfall anomalies corresponding to warm and cold events in the different oceanic basins, using composite analysis. This second approach gives a clearer idea of the relationships between tropical SST anomalies and rainfall anomalies in the Amazon basin.

These two cross-analyses are done in order to verify whether or not all rainfall anomaly patterns are associated with SST anomalies.

3.1. Spatial organization of rainfall anomalies

In order to identify the main spatial patterns of rainfall anomalies in the Amazon basin, we computed a cluster analysis on the monthly rainfall anomalies of each quarter, using Ward's method (see description in

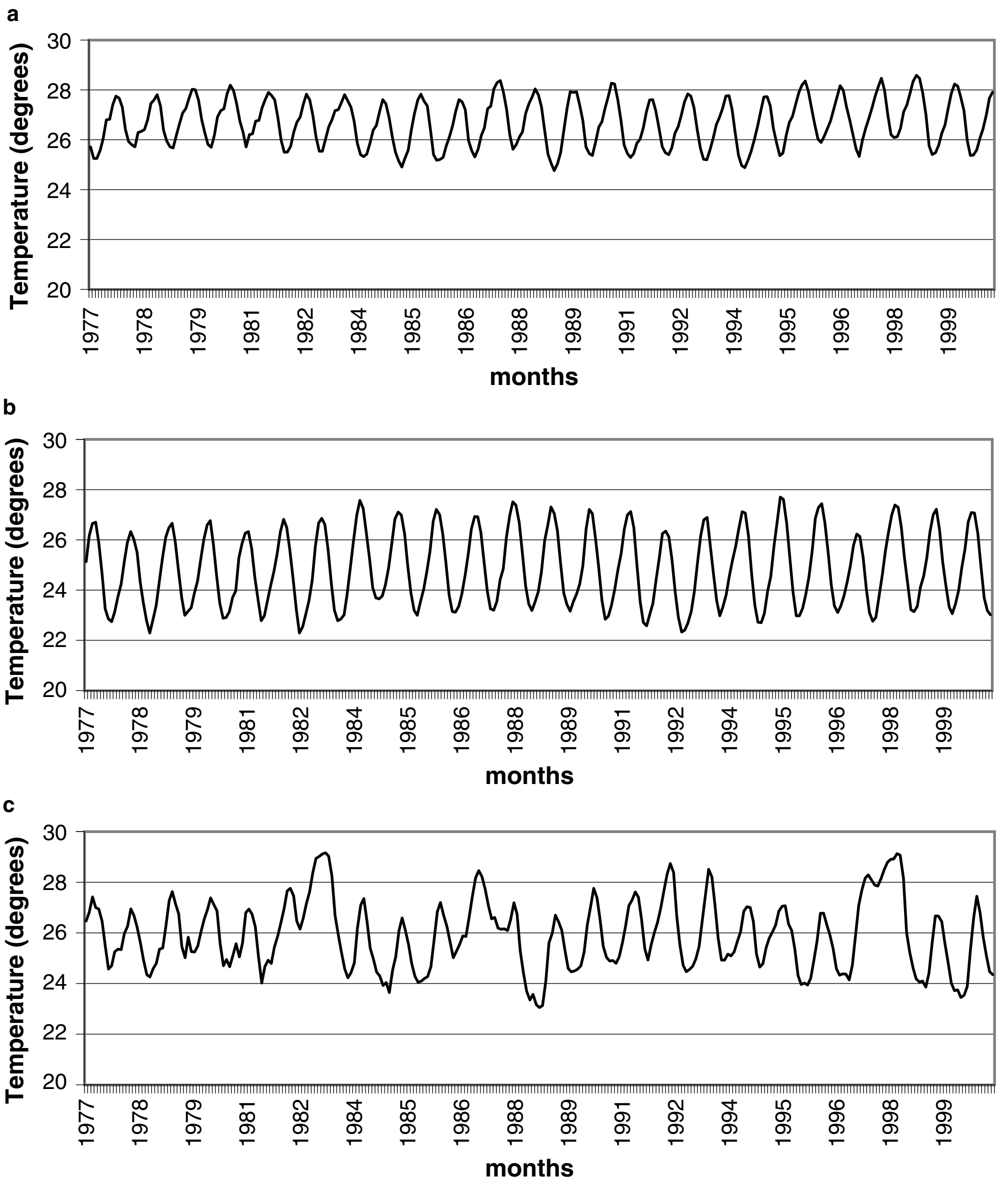


Figure 3. Monthly 1977–2000 SSTs in the (a) NATL basin (5–20 °N, 60–30 °W), (b) SATL basin (0–20 °S, 30 °W–10 °E), and (c) Niño3 region (5 °S–5 °N, 150–90 °W)

Section 2.1). The main classes of rainfall anomalies are presented in Figures 5 to 8. The mean SST anomalies corresponding to each class are shown in Table II.

Three of the quarter periods present a class with negative rainfall anomalies encompassing the majority of the Amazon basin (Figures 5(a), 6(a), and 8(a)). The negative anomalies are stronger in the northeastern basin in the summer (Figure 5(a)) and in the eastern basin in the autumn (Figure 6(a)). They are associated with strong positive SST anomalies in the PAC (El Niño events; Table II). In autumn (Figure 6(a)) and spring (Figure 8(a)), important negative rainfall anomalies in the southeastern basin are also concomitant with abnormal warm SSTs in the northern Atlantic.

Table I. Warm (w) and cold (c) events during the quarters and hydrological years (September–October) of the 1977–99 period. 1977 is for the hydrological year 1977–78 and the 1977 DJF quarter is for the December 1977 to February 1978 period

Year	DJF			MAM			JJA			SON			Hydrological year (Sept.–Oct.)		
	SATL	NATL	PAC	SATL	NATL	PAC	SATL	NATL	PAC	SATL	NATL	PAC	SATL	NATL	PAC
1977	c												c		
1978	c			c			c	c		c			c		
1979	c	w			w									w	
1980	c	w			w			w					c	w	
1981				c	w										
1982		c	w	c			c		w	c	c	w	c		w
1983	w				w	w	c		w		c		w	c	
1984	w	c	c	w	c		w	c	c	w	c	c	w	c	c
1985		c	c		c	c			c			c		c	
1986		c	w		c			c			c				w
1987	w	w				w	w	w	w	w	w	w	w	w	
1988	w	c	c	w		c	w	w	c			c	w	c	c
1989	c				c	c	w								
1990											w				
1991			w		c			c	w	c	c		c		w
1992	c	c		c		w	c			c			c	c	
1993	w	c				w				w				c	
1994					c			c							
1995		w	c	w				w			w	c	w	w	c
1996	c	w	c	w	w	c	w						c		
1997	w	w	w	c			c		w	w	w	w	w	w	w
1998			c	w	w	w	w	w			w	c		w	c
1999		w	c			c	w		c		w	c		w	c

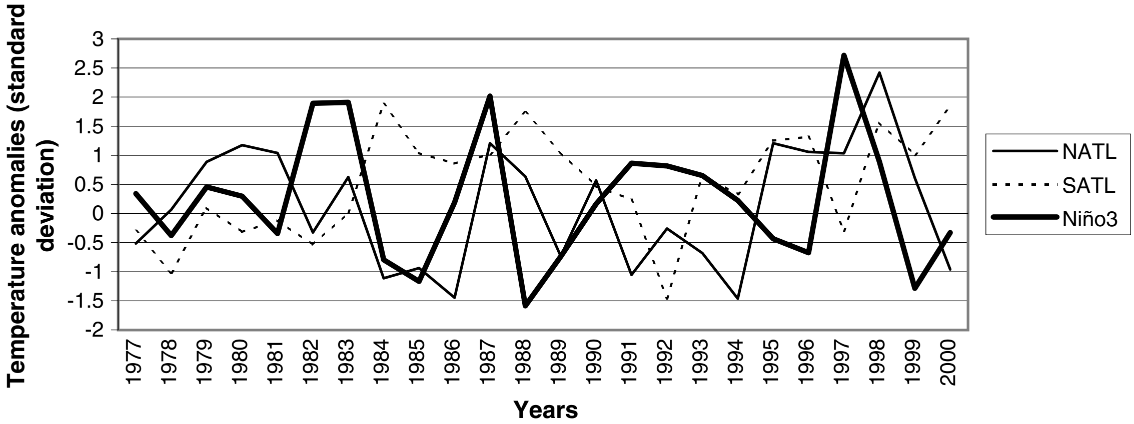


Figure 4. Annual 1977–2000 SST anomalies (standard deviation) in the NATL (5–20 °N, 60–30 °W), the SATL basin (0–20 °S, 30 °W–10 °E), and the Niño3 region (5 °S–5 °N, 150–90 °W)

During autumn (Figure 6(b)), winter (Figure 7(a)), and spring (Figure 8(b)), slight negative (positive) anomalies in the NA (SA) basin are associated with small positive SST anomalies in the Pacific and cold anomalies in the southern Atlantic (Table II).

A cluster with excess of rain prevailing in the eastern basin can be found in summer (Figure 5(b)), autumn (Figure 6(c)), and spring (Figure 8(c)). This structure is associated in autumn and spring with warm SSTs in the southern Atlantic and with cold SSTs in the PAC (La Niña) and the northern Atlantic. In DJF this structure is poorly associated with SST anomalies.

In summer (Figure 5(c)) and winter (Figure 7(b)) a bipolar configuration, with an excess of rain in the northern part of the basin and a deficiency in the south, is associated with cold SSTs in the PAC (La Niña).

Other rainfall spatial structures with very strong excesses of rain in the eastern part of the Amazon basin in summer (Figure 5(d)) and in most of the basin in winter (Figure 7(c)) are rarely observed, so that they cannot be associated with any SST anomaly.

Table II. SST anomalies (in degrees) in the three oceanic basins corresponding to each cluster. Each cluster has the name of the corresponding figure. The seasonal cluster analyses are taken from monthly rainfall anomalies

	class	No. of months	Niño3	NATL	SATL
DJF	Figure 5(a)	15	1.2	0.1	0.4
	Figure 5(b)	13	−0.1	−0.3	0.0
	Figure 5(c)	37	−0.6	0.2	−0.2
	Figure 5(d)	3			
MAM	Figure 6(a)	18	0.7	0.6	−0.2
	Figure 6(b)	23	0.3	0.1	−0.5
	Figure 6(c)	26	−0.7	−0.4	0.5
JJA	Figure 7(a)	34	0.4	0.1	−0.4
	Figure 7(b)	24	−0.4	0.0	0.5
	Figure 7(c)	9			
SON	Figure 8(a)	23	0.0	0.3	0.1
	Figure 8(b)	23	0.4	−0.1	−0.5
	Figure 8(c)	20	−0.3	−0.4	0.4

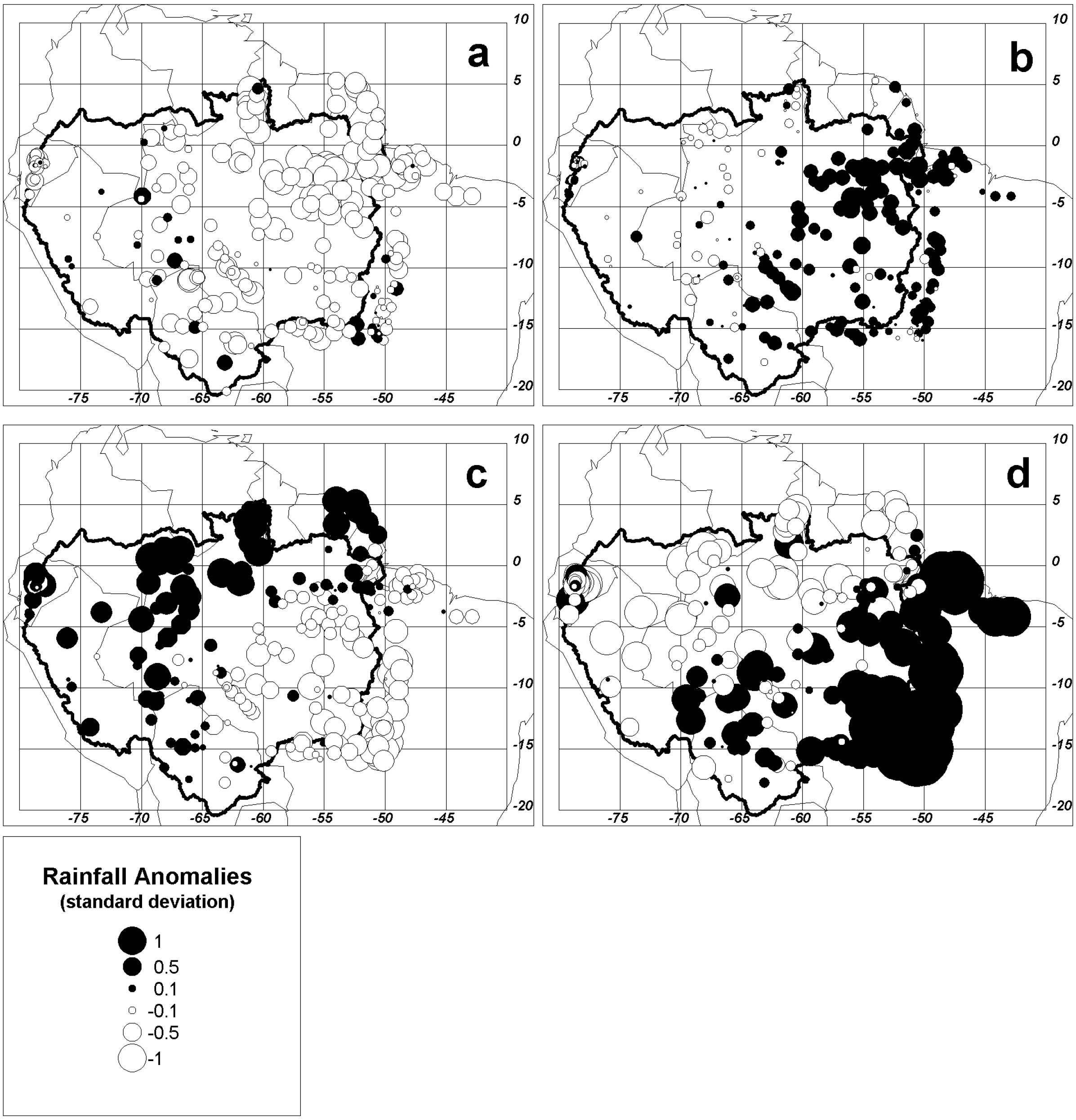


Figure 5. Four upper classes resulting from a hierarchical cluster analysis on the 1977–99 December, January, and February rainfall anomalies (standardized data)

In conclusion, global deficits of rain, with the higher rates in the NEA and/or the eastern Amazon, are associated with El Niño, mainly during the summer and autumn seasons, which receive the highest quantity of rain. When the SST anomalies in the PAC are weaker and when the southern Atlantic is cold, a north–south pattern of rainfall anomalies, with a weaker deficit in the northern basin and an excess of rain in the south, is observed. Warm SSTs in the NATL basins are also a frequent feature associated with dry conditions, especially in the southeastern Amazon basin.

Excesses of rain in the eastern Amazon basin or in its northern part are often associated, during the rainiest seasons, with La Niña and with warm SSTs in the southern Atlantic and cold SSTs in the northern Atlantic.

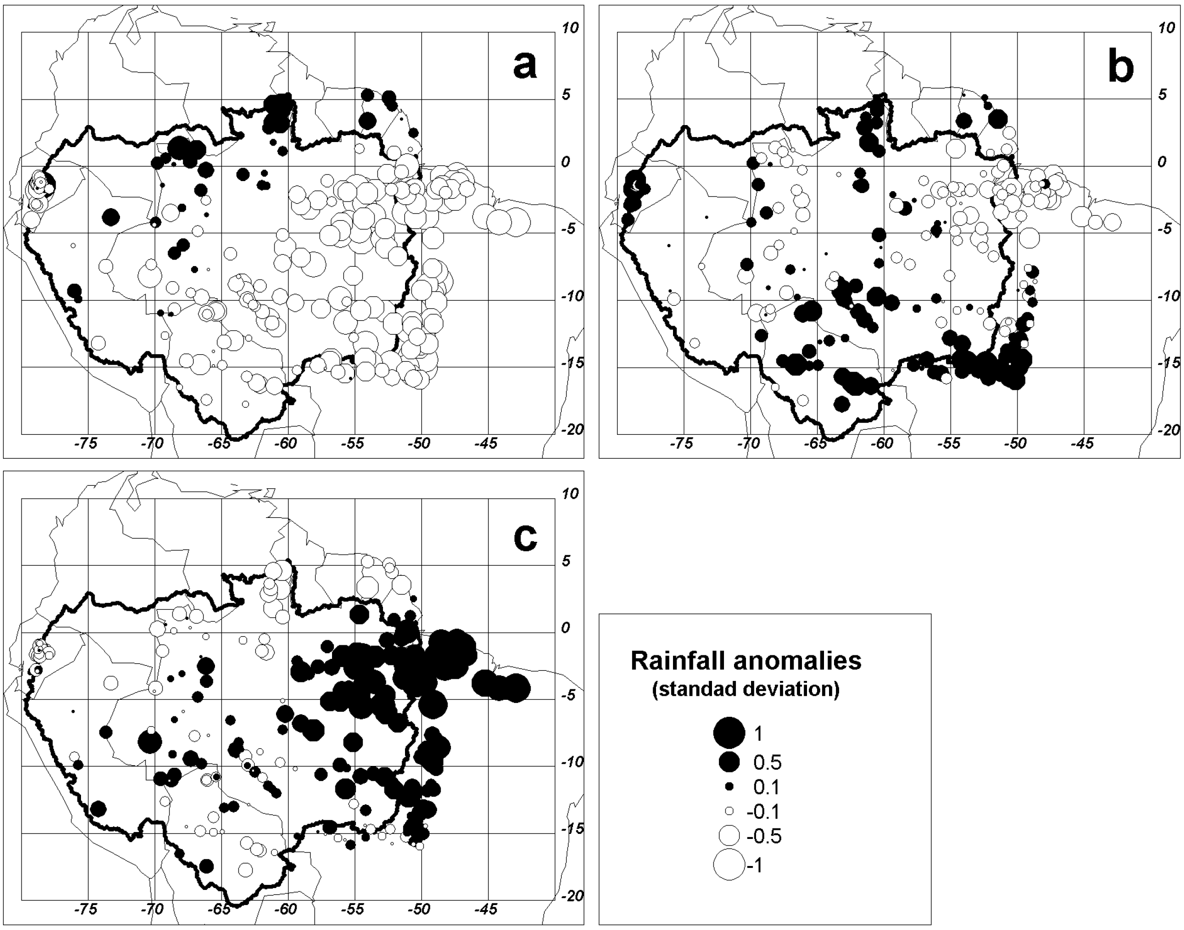


Figure 6. Three upper classes resulting from a hierarchical cluster analysis on the 1977–99 March, April, and May rainfall anomalies (standardized data)

Some spatial patterns of rainfall are not generally associated with any SST anomaly. They are:

- positive anomalies in the eastern and southern part of the basin during the summer, the rainiest season; and
- intense positive anomalies in the whole basin in the winter, the driest season with the highest rainfall variability.

3.2. *Rainfall anomalies associated with SSTs in the oceanic basins*

Composite analysis is used to study time–space associations between rainfall and SST anomalies. Composites of simultaneous annual and 3-month (seasonal) rainfall anomalies are computed for each station for each oceanic event. Warm and cold events in the oceanic basins are described in Section 2.2 and listed in Table I.

We first examine oceanic event results per basin, taking into account that oceanic events often occur simultaneously (e.g. warm SSTs in the southern Atlantic and cold SSTs in the northern Atlantic, warm SSTs in both Atlantic basins, warm southern Atlantic and La Niña, El Nino and cold southern Atlantic, etc.) and that each event is not always clearly separable from others. As an exception, the cases of years with cold events in SATL and no other oceanic anomaly are frequent enough to be analysed. Then we look at information concerning some combinations of events that occurred at least twice during the 1977–99 period. An anomaly

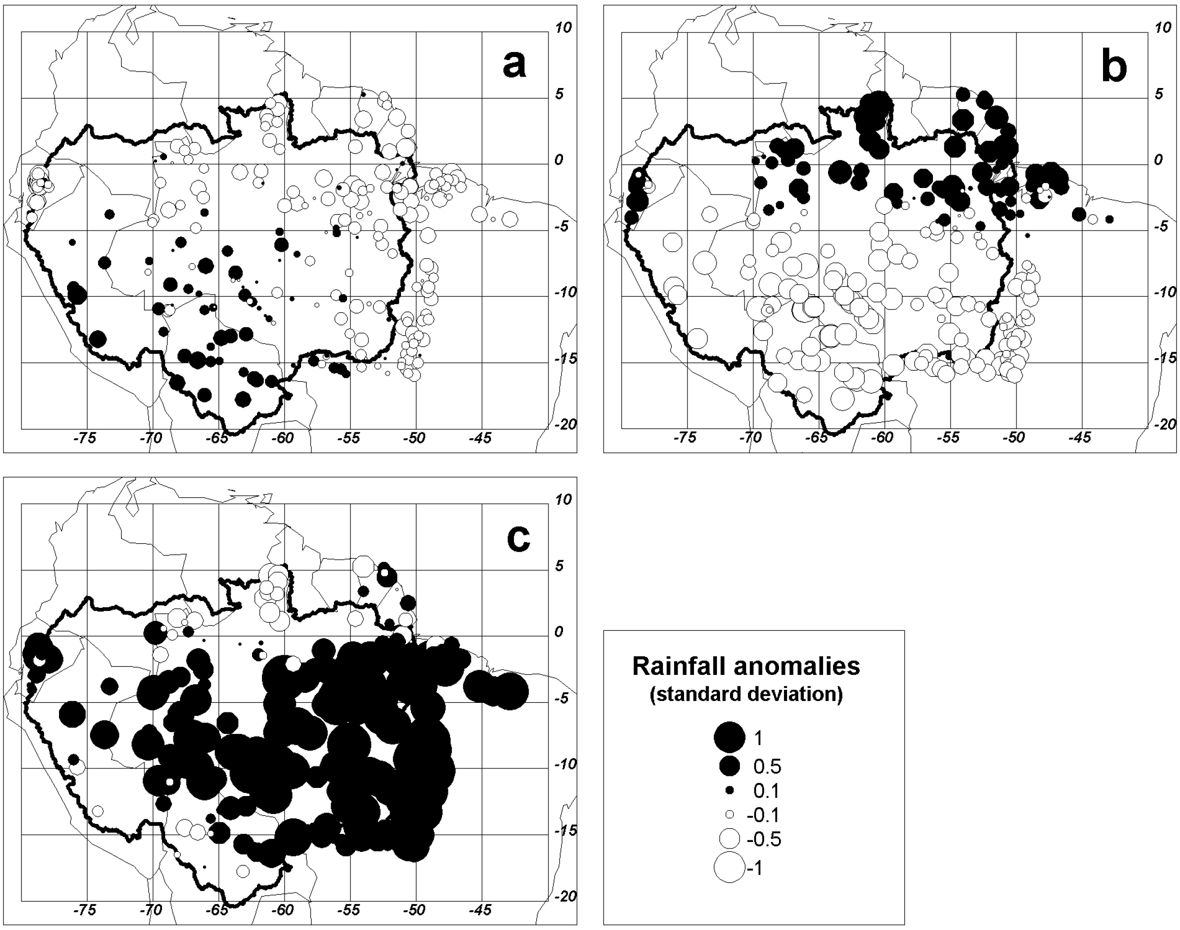


Figure 7. Three upper classes resulting from a hierarchical cluster analysis on the 1977–99 June, July, and August rainfall anomalies (standardized data)

is taken into account only if it is significant at the 0.1 level for a two-tailed test of the null hypothesis of no difference from the 1977–99 mean.

3.2.1. Per basin analysis. The rainfall anomalies associated with the oceanic events are presented in Figures 9 to 12. The percentage of significant anomalies in the whole basin for each event and each season is shown in Table III.

Table III. Percentage of stations with significant rainfall anomalies, for each oceanic event (El Niño, La Niña, warm and cold SATL, warm and cold NATL) during the hydrological year (September–October) and each season; w, warm; c, cold

	El Niño	La Niña	SATLw	SATLc	NATLw	NATLc
DJF	35	16	11	6	5	2
MAM	27	19	12	12	20	20
JJA	21	21	10	17	25	7
SON	24	9	4	27	13	4
Hydrological year (Sept.–Oct.)	29	18	8	22	4	13

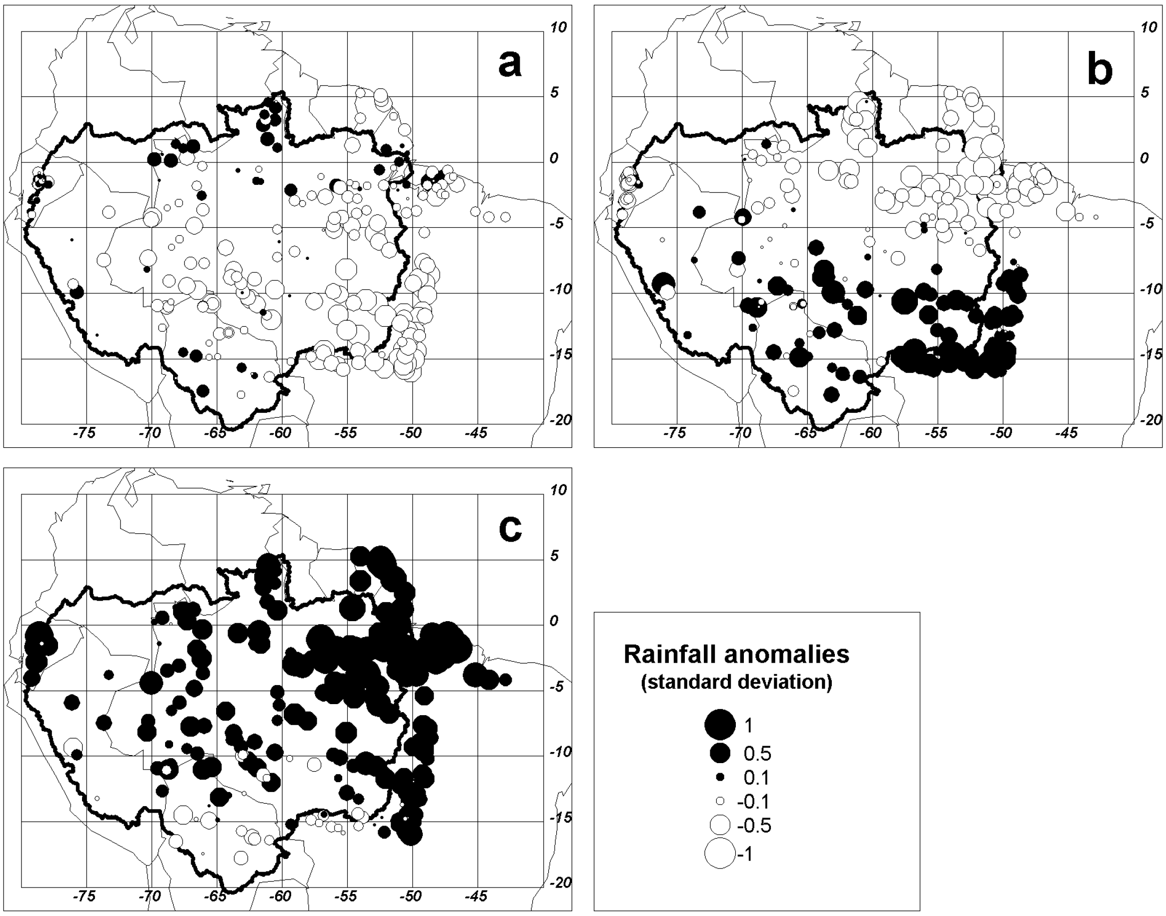


Figure 8. Three upper classes resulting from a hierarchical cluster analysis on the 1977–99 September, October, and November rainfall anomalies (standardized data)

3.2.1.1. PAC: During an average September–August El Niño year, the rainfall total is smaller than the 1977–99 mean at 82% of the stations of the basin. Significant negative anomalies are observed at 29% of the stations. They are located mainly north of 7 °S and east of 60 °W, in the NEA region, where 72% of the anomalies are significant (Figure 9(a)). In that region, the negative rainfall anomalies prevail during the whole year, especially in summer at the peak of an El Niño event, but the mean annual anomaly is higher (−1.1 standard deviation) than the mean summer anomaly (−0.7 standard deviation).

The regions with significant anomalies vary during the year. They are spread across the whole Amazon basin in summer: more than a third of the stations of the Amazon basin have significant negative anomalies (Figure (9b)). In autumn, the deficit of rain is an eastern Amazon feature (Figure (9c)) and a northern one in spring (not shown). Excesses of rain are observed in the Ecuadorian Amazon basin on an annual time scale; at many stations they are significant in autumn. On an annual time scale and in autumn and winter, non-significant positive anomalies are also found in the southwestern Amazon basin (Figure 9(a) and (c)).

During a mean La Niña year, significant anomalies are observed at 18% of the stations of the Amazon basin. Most of them are positive and located in the NEA region, east of 60 °W and north of 5 °S, where 38% of the anomalies are significant (Figure 10(a)). The mean annual anomaly in the NEA region is one standard deviation. The 3-month analysis (Table III) shows that during La Niña positive rainfall anomalies prevail from summer until winter in the NEA region. The anomalies are located in the northern part of the basin in summer and in winter (Figure (10c)) and in its eastern part in autumn (Figure (10b)). Negative anomalies are found in the SA and in the Peruvian Amazon basin on an annual time scale (Figure 10(a)). In winter,

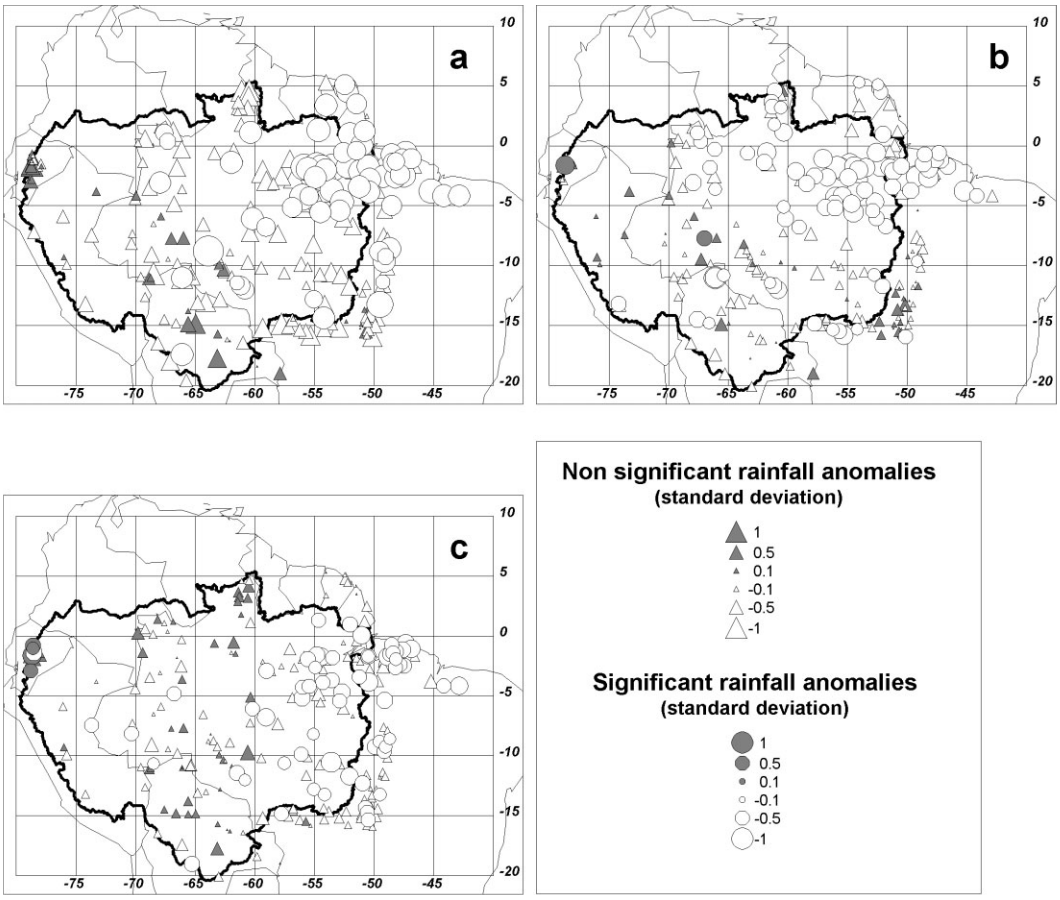


Figure 9. El Niño rainfall anomalies composite during (a) the hydrological year (September–October), (b) summer: DJF, (c) autumn: MAM. Circles represent the anomalies that are significant at the 90% confidence level. The non-significant anomalies are represented by triangles

significant deficits of rain in the SA are observed at 23% of the stations (Figure 10(c)) and they contribute greatly to the strong percentage of significant anomalies (Table III).

In conclusion, the two phases of the SO are associated with opposite rainfall anomalies, mainly located in the NEA basin. The deficit of rain during El Niño is nearly global in the NEA region during the whole year and widely spread in the rest of the basin, particularly in summer. The excess of rainfall during La Niña is confined to the NEA region, where it is significant at a small number of stations.

During El Niño events, the main anomalies are well defined during the whole year, suggesting that there is a shorter than normal rainy season in the NEA. During La Niña the deficit is observed during the core of the rainy season, in summer and autumn, and in winter, suggesting an early end of the rainy season.

During El Niño and La Niña, rainfall anomalies in the Amazon basin have the same signs as those documented for northern South America and for the Nordeste of Brazil. Moreover, they have the same seasonality as those in neighbouring regions: in the eastern Amazon the anomalies are centralized around the autumn, as in the Nordeste (Aceituno, 1988; Uvo *et al*., 1998), and in the NA they occur from the boreal summer until the austral summer as in northern South America (Aceituno, 1988).

In a few locations of the SA, La Niña is associated with a deficit of rain, as already documented by Ronchail (1998). In addition, excesses of rain are observed during some El Niño events (1982–83, 1991–92) in the SA, but are not significant for the 1977–99 period. As these last two results refer to the wintertime, the rainfall anomalies could be attributed to a deficit (enhancement) of the activity of extra-tropical perturbations during La Niña (El Niño). It can be noticed that the ENSO-related rainfall variability observed in the SA

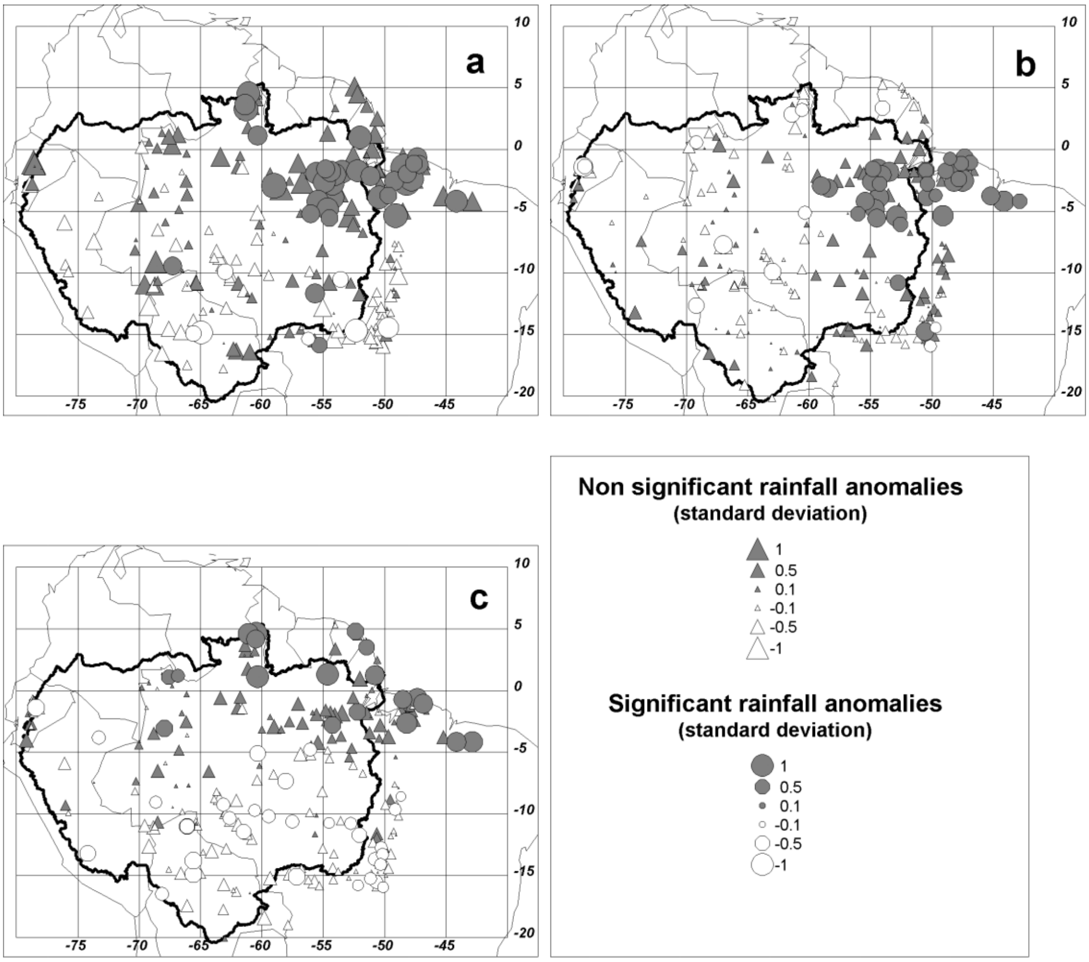


Figure 10. La Niña rainfall anomalies composite during (a) the hydrological year (September–October), (b) autumn: MAM, (c) winter: JJA. Circles represent the anomalies that are significant at the 90% confidence level. The non-significant anomalies are represented by triangles

basin is partly similar to that described for southeastern South America (SESA) (Aceituno, 1988; Montecinos *et al.*, 2000; Grimm *et al.*, 2000).

In the Ecuadorian Amazon basin (lowlands and Andean eastern slopes), some evidence of above-normal rainfall is observed during El Niño.

3.2.1.2. SATL and NATL: On an annual time scale, warmer than usual temperatures in the southern Atlantic are associated with significant positive rainfall anomalies at a few stations located near the mouth of the Amazon River. More significant cases are found during the MAM period at the peak of the rainy season (Table III, Figure 11(a)).

On an annual time scale, the signal associated with a colder than normal SATL is stronger: significant anomalies are found at 22% of the stations of the Amazon basin (Table III). The anomalies have a bipolar organization: in the northern and the northeastern regions of the Amazon basin a deficit of rain prevails (−0.9 standard deviation) and is significant at 58% of the NEA stations, whereas in the southern basin an excess of rain dominates but is hardly significant (Figure 11(b)). This annual pattern is also developed in autumn, winter, and especially in spring, although the negative anomalies in the northeastern basin are weaker than the annual ones (−0.6 standard deviation in spring). The extension of significant positive anomalies in the SA is greater in spring and summer.

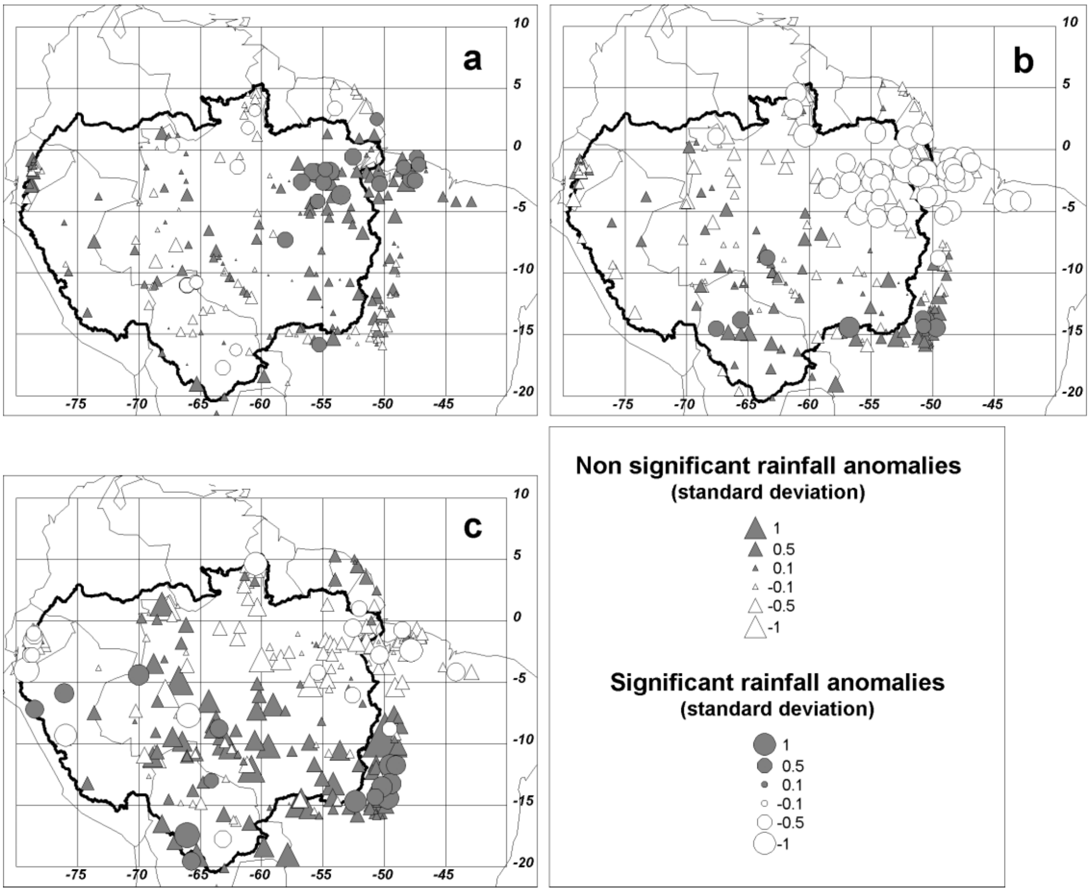


Figure 11. Rainfall anomalies composite during (a) a warm SATL autumn (MAM), (b) cold SATL years (September–August), and (c) cold SATL years that are not associated with other SST anomalies. Circles represent the anomalies that are significant at the 90% confidence level. The non-significant anomalies are represented by triangles

When the southern Atlantic is cold and no other oceanic anomaly is observed, rainfall anomalies in the northeastern basin (dryness) weaken compared with the anomalies computed for all the cases in which SATL is involved (Figure 11(c)). This may be due to the exclusion of the years when cold SSTs in the southern Atlantic are associated with El Nino. We can conclude that a cold southern Atlantic has a smaller effect than El Niño on rainfall in the NEA. On the other hand, an excess of rain in the SA, in particular in the southeastern Amazon, is more often significant and stronger when considering isolated cold SATL cases. The deficit of rain in the Ecuadorian Amazon (Figure 11(c)) is in agreement with Vuille *et al*. (2000).

A cold NATL year is associated with positive rainfall anomalies in the NEA basin, where they are significant at 25% of the stations (not shown). The anomalous rainfall is detected mostly in autumn, the rainy season of that region, and is equivalent to 0.5 of a standard deviation (Figure 12(a)). Negative rainfall anomalies are observed in some northern and western locations of the Amazon basin.

On an annual time scale, very few significant rainfall anomalies are associated with a warmer than usual NATL (not shown). However, in autumn, negative anomalies (−0.5 standard deviation) are observed in the northeastern part of the Amazon basin, where 41% of the anomalies are significant, and in the southeastern Amazon (Figure 12(b)). In winter, a significant deficit of rain is observed in most of the basin, especially in its southern part (Figure 12(c)).

In conclusion, opposed rainfall anomalies in the NEA are associated with opposed SST anomalies in the SATL, with a deficit of rain when the southern Atlantic is cold and an excess of rain when the southern

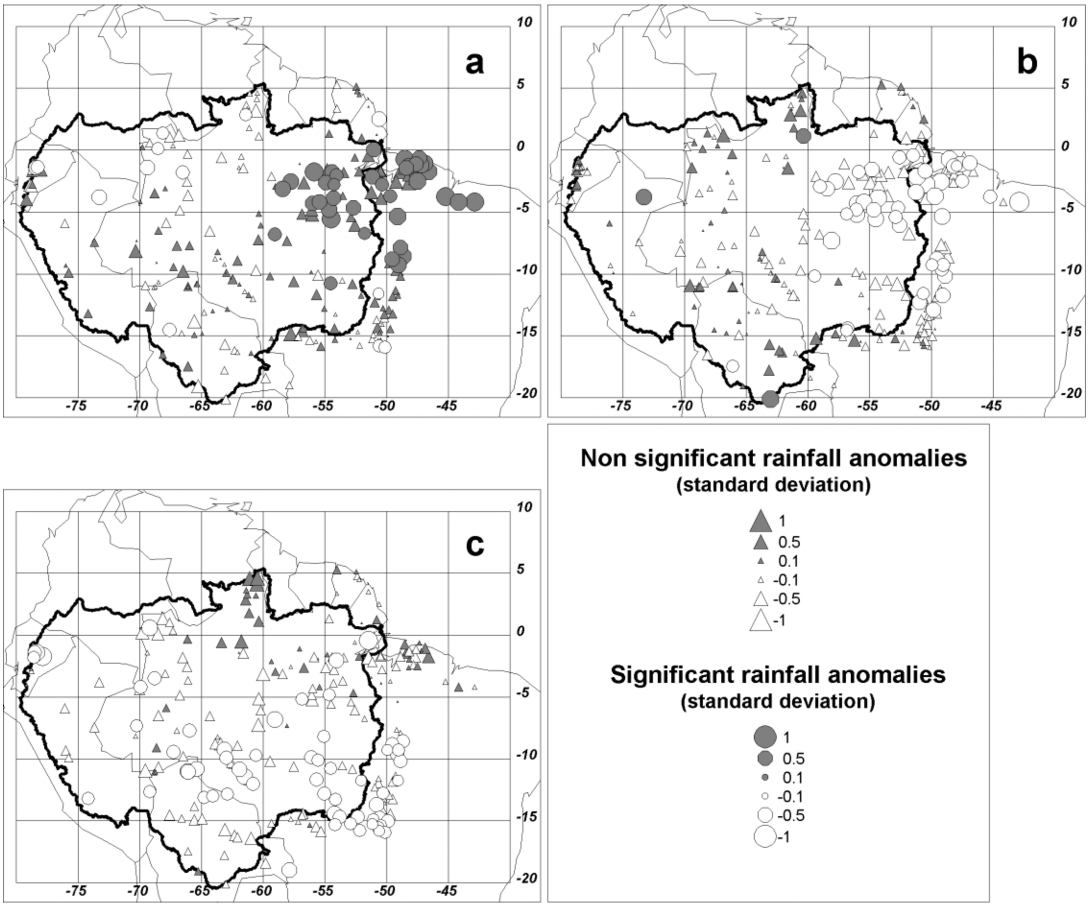


Figure 12. Rainfall anomalies composite during (a) a cold NATL autumn (MAM), (b) a warm NATL autumn, and (c) a warm NATL winter (JJA). Circles represent the anomalies that are significant at the 90% confidence level. The non-significant anomalies are represented by triangles

Atlantic is warm, this last signal being much weaker than the former. In the SA basin, a widely spread but non-significant excess of rain is observed when the southern Atlantic is cooler than normal.

In autumn, opposed rainfall anomalies in the NEA are associated with opposed SST anomalies in the NATL: an excess (a deficit) of rain is related to colder (warmer) northern Atlantic temperatures. Winter is dry in most of the basin when the northern Atlantic is warmer than usual.

3.2.2. Combined basin analysis. For the short 1977–99 period, it is normally difficult to encounter enough samples of specific combinations of events in the three oceanic basins to respond to the following questions:

- Is the El Nino-related deficit of rain in the NEA basin lower when warm SSTs prevail in the southern Atlantic?
- Or, on the contrary, is the deficit of rain reinforced when El Niño combines with cold SSTs in the southern Atlantic?

However, available data, as shown in Table IV, allow us to attempt to answer these and other related questions. The combined events are analysed on an annual time scale.

The combined effects of El Niño and cold SSTs in the SATL are a reinforcement of the negative anomalies in the NEA (−1.3 standard deviation) compared with El Niño or cold SATL events (Figure 13(a)). This

Table IV. Number of events and number and percentage of stations with significant anomalies for different combinations of oceanic events; w, warm; c, cold

Combined oceanic events	No. of events	Significant anomalies	
		No.	%
SATLc + El Niño, 1982, 1991	2	71	29
SATLw + NATLc, 1983, 1984, 1988	3	49	20
SATLw + NATLw, 1987, 1995, 1997	3	24	10
NATLw + Niña, 1995,1998,1999	2	47	19

is consistent with Molinier *et al.* (in press). In the SA, the occurrence of positive rainfall anomalies are more frequent than during cases of El Niño (Figure 9(a)) and less frequent than during cases of cold SATL (Figure 11(b)). These results confirm that rainfall anomalies in the SA basin are associated with cold events in the southern Atlantic.

Cold SSTs in the NATL and warm SSTs in the SATL combine with efficiency as they are associated with positive rainfall anomalies in the NEA that are stronger (1.1 standard deviation) and much more widely extended than those associated with single cold NATL or warm SATL events (Figure 13(b)). This result is consistent with the findings by Nobre and Shukla (1996).

The last two combined oceanic events are usually associated with inverse rainfall anomalies in the NEA (Table IV). In the first case, the excess of rain in NEA, usually associated with warm SSTs in the SATL, is still apparent but spatially reduced and non-significant, and dry conditions, usually associated with warm SSTs in the northern Atlantic, prevail in most of the southern basin (Figure 13(c)). In the second case (Figure 13(d)), a similar diagnosis can be made: the association of La Niña and warm SSTs in the NATL seems to reduce the excess of rain in the NEA and to reinforce the rainfall deficit in the southern basin, as has already been noted by Pezzi and Cavalcanti (2001).

In conclusion, some oceanic events associated with the same (different) sign rainfall anomalies in the NEA do increase (decrease) the rainfall anomaly when they are combined. This is consistent with the findings of Uvo *et al.* (1998) in the Nordeste.

4. FURTHER COMMENTS AND CONCLUSION

The relationships between tropical SST anomalies and rainfall anomalies in the Amazon basin have been studied during the 1977–99 period using cluster and composite analyses. Both of them show the principal characteristics of the Pacific and Atlantic SST-related rainfall anomalies. Most of the results of both analyses are consistent. However, when focusing on warm or cold oceanic events, the composite analysis more accurately describes rainfall anomalies associated with SST anomalies, and underlines the particular nature of the NEA. The cluster analysis gives equal importance to all the years of the 1977–99 period and to all the stations of the Amazon basin. It is probable that the results have mixed together different signals and underlines the complex nature of rainfall origins in certain regions of the Amazon basin. The cluster analysis has been useful in discovering patterns of rainfall anomalies that are not associated with tropical SSTs and also, as is detailed further, that not all dry or wet events in the NEA are associated with SST anomalies.

The main results of the composite analyses are summarized in Figure 14. They are proposed for three of the four regions described in Section 2.1: NEA, NA, and WA. Ecuadorian stations have been excluded from the WA because they have some unique features. They are treated separately. The different behaviours of the southwestern and southeastern parts of the Amazon basin also justify the partitioning of these regions. The mean rainfall anomalies for each oceanic event and for each season are given for the six resulting regions of the Amazon basin. The annual and seasonal standard deviations are provided in order to evaluate the anomalies in millimetres.

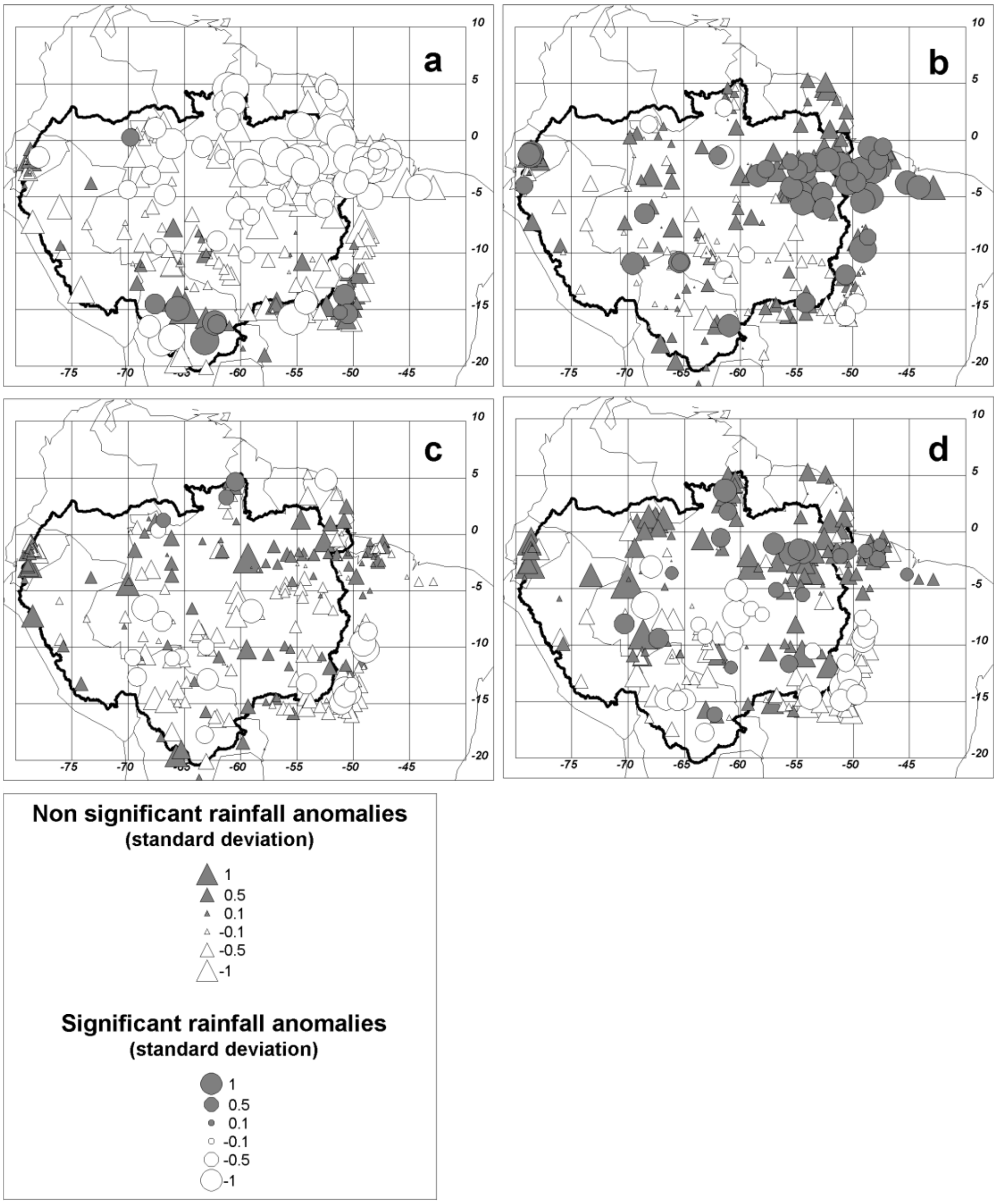


Figure 13. Rainfall anomalies composite during the annual (September–August) following combinations: (a) El Niño + cold SATL, (b) warm SATL + cold NATL, (c) warm SATL + warm NATL, (d) La Niña + warm NATL. Circles represent the anomalies that are significant at the 90% confidence level. The non-significant anomalies are represented by triangles

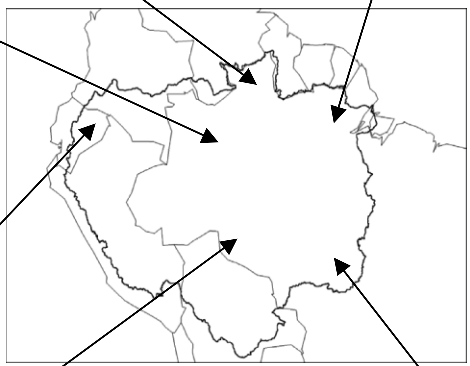
4.1. In the NEA basin

The main significant SST-related rainfall anomalies in the Amazon basin occur in the NEA basin, north of 5 °S and east of 60 °W, i.e. in a near oceanic and equatorial position. This has already been documented by Roucou (1997) and is consistent with Liebmann and Marengo (2001) and Molinier *et al*. (in press).

NA	Hyd. Year	DJF	MAM	JJA	SON
El Niño		<u>*-0.6*</u>		*-0.6*	<u>*-0.6*</u>
La Niña		<u>**0.7**</u>		**0.8**	
SATL c				<u>*-0.7*</u>	<u>*-0.6*</u>
SATL w					
NATL c					
NATL w					
STD	423	154	198	191	145

NEA	Hyd. Year	DJF	MAM	JJA	SON
El Niño	<u>*-1.1*</u>	<u>*-0.7*</u>	<u>*-0.6*</u>	*-0.6*	<u>*-0.7*</u>
La Niña	<u>**1**</u>	**0.5**	<u>**0.6**</u>	**0.7**	
SATL c	<u>*-0.9*</u>		*-0.5*	*-0.5*	<u>*-0.6*</u>
SATL w			**0.5**		
NATL c	**0.9**		<u>0.5</u>		
NATL w			<u>-0.5</u>		
STD	808	393	464	222	181

WA	Hyd. Year	DJF	MAM	JJA	SON
El Niño		*-0.6*	*-0.5*		*-0.5*
La Niña					
SATL c					
SATL w					
NATL c					
NATL w					
STD	329	172	203	190	160



Ecuador	Hyd. Year	DJF	MAM	JJA	SON
El Niño			***0.33***		
La Niña					
SATL c					
SATL c only	*-0.7*				
SATL w					
NATL c					
NATL w					
STD	200	76	96	53	70

SW Amaz.	Hyd. Year	DJF	MAM	JJA	SON
El Niño		*-0.5*			
La Niña				*-0.5*	
SATL c					**0.5**
SATL w					
NATL c					
NATL w				*-0.4*	
STD	329	196	134	53	125

SE Amaz.	Hyd. Year	DJF	MAM	JJA	SON
El Niño	*-1*	*-0.6*	*-0.5*	*-0.4*	
La Niña				*-0.4*	
SATL c					
SATL c only	**0.6**				
SATL w					
NATL c			**0.3**		
NATL w			*-0.5*	<u>*-0.4*</u>	
STD	376	246	161	35	130

Figure 14. Main SST-related rainfall anomalies (standard deviation) in the Amazon basin, by region: c, cold; w, warm; 'SATL c only', cold events in the SATL that do not combine with other oceanic events. Underlined data mean that more than 40% of the stations have significant anomalies; non-underlined data mean that the percentage of stations with significant anomalies is between 20 and 40%. Bold data are positive, italic data are negative. STD denotes standard deviation. The values of standard deviation are in millimetres

On an annual time scale, abnormally wet conditions in the NEA are associated with La Niña and relatively cold SSTs in the NATL, whereas a relative dryness is related to El Niño and cold SSTs in the SATL.

In autumn, warm events in the SATL (NATL) are also associated with positive (negative) rainfall anomalies in the NEA. Generally, the strongest signals in the NEA are observed in autumn, the rainiest season, with the exception of spring for cold events in the SATL and summer for El Niño (Figure 14).

El Niño events are associated with the strongest, the most widely spread, and the longest-lasting anomalies: on an annual time scale, more than 70% of the stations in the NEA have a significant deficit of rainfall higher than one standard deviation. The beginning of the rainy season is delayed and its end occurs earlier, as mentioned by Marengo *et al*. (2001), so that the El Niño-related rainfall anomalies involve the whole year. The negative anomalies are further reinforced when El Niño is associated with cold SSTs in the SATL, as described by Pezzi and Cavalcanti (2001) in a modelling experiment.

On the other hand, the rainfall anomalies associated with La Niña and SST anomalies in the Atlantic basins are weaker and less widely spread in the NEA basin. The La Niña-related anomalies are observed during three quarters of the year (with a delayed ending of the rainy season), whereas other anomalies only last one or two quarters. The result is that the spatial and temporal impacts of oceanic events associated with excesses of rain are smaller than those associated with dryness. It is noticeable that the combination of oceanic events associated with an excess of rain in the NEA, as cold SSTs in the NATL and warm SSTs in the SATL, increases the positive rainfall anomalies, as commented on by Nobre and Shukla (1996). However, the combination of oceanic events associated with opposed rainfall anomalies in the NEA tends to minimize the anomalies.

The ENSO-related rainfall anomalies in the NEA region are also observed in the nearby regions of the Amazon basin, in the summer, autumn and winter of the respective hemispheres. In the NA (in the Northern Hemisphere) both phases of the SO are important features, whereas only the El Niño phase is important in the southeastern Amazon (Figure 14). In consequence, one can observe a time–space continuity between the El Niño-related rainfall anomalies in the NEA, those in the NA and southeastern Amazon, and those in northern South America and in the Nordeste of Brazil. Furthermore, during the boreal summer and autumn of a cold SATL event, negative anomalies are registered in the NA as in NEA.

The current understanding of the associations between rainfall anomalies in northeastern Brazil and SSTs in the tropical ocean stems from Hastenrath and Heller (1977). They explained that Secas in the Nordeste are associated with enhanced (weakened) surface pressure and relatively cold (warm) water in the SATL (NATL). The pressure anomaly field explains enhanced (weakened) southerly (northerly) trade winds, resulting in a northward-displaced intertropical convergence zone (ITCZ). They also underlined the relationship between Secas and El Niño events in the Pacific. Aceituno (1988) described similar features associated with diminished rainfall in the Amazon basin. Marengo (1992) noted the strong North Atlantic high, the accelerated northeast trades during cold SST events in the northern Atlantic, and the enhanced boundary-layer moisture transport from the North Atlantic into the Amazon. Nobre and Shukla (1996) associated the negative (positive) rainfall anomaly in the Amazon region and in the Nordeste, during autumn, with an early withdrawal of the ITCZ toward the warm SSTs over the northern (southern) Atlantic. Kousky *et al.* (1984), followed by Marengo and Hastenrath (1993), described a direct relationship between the SST anomalies in the eastern Pacific and the rainfall deficit in northeastern Brazil with, during El Niño years, a strong Walker-type circulation with sinking motion over the eastern Amazon, northeast Brazil and the PAC. Attempts to explain the ENSO–related SST variability in the tropical Atlantic Ocean were made by many. Among the most notable, Enfield and Mayer (1997) emphasized the dynamics of trade winds and Hastenrath (2001) identified Atlantic upper-air mechanisms through which the ENSO affects surface pressure and SST fields in the tropical Atlantic.

When considering the results of the cluster and the composite analyses, it appears that some deficits and excesses of rain in the NEA are not associated with SST anomalies in the tropical oceans. Table V displays the percentage of months with deficit or excess of rain in the NEA that occurs during oceanic events and the percentage of months during 'normal' oceanic periods (without an SST anomaly). Dryness can hardly be observed in summer when there is no SST anomaly, especially in the Pacific. On the other hand, during the other seasons of the year, nearly a third of the months with rainfall deficits in the NEA are observed during 'normal' oceanic periods. In autumn, an excess of rain is closely related to oceanic events. However, in spring and summer, 50% of the wet months occur without an SST anomaly in the tropical Pacific and Atlantic oceans.

4.2. The SA and WA basins

There are few spatially coherent and/or significant SST-related rainfall signals in the WA and SA basins (Figure 14). According to Moron *et al.* (1995) and Fu *et al.* (1999), land surface condition variability in the NEA is limited and convection is more affected by the changes of the SST in the adjacent oceans. On the other hand, the weakness of the rainfall–SST relationships in the SA may be due to the fact that land surface temperatures vary greatly and thus control the convection. Also, synoptic factors are likely to be important in the SA and WA, which explain rainfall variability.

Nonetheless, tendencies toward dryness have been identified during El Niño in the SA and WA (summer), during La Niña south of 10 °S (winter), and when the northern Atlantic is anomalously warm in the southern

Table V. Percentage of months with deficit or excess of rain in the NEA that occurs during warm or cold oceanic events or during periods without an SST anomaly. The sums of the percentages can be greater than 100%, as a rainfall anomaly can be associated with more than one SST anomaly. Rainy and dry months are those defined by the cluster analysis

	Rain deficit in NEA			
	El Niño	Cold SATL	Warm NATL	Without SST anomalies
DJF	60	13	33	13
MAM	44	22	44	28
JJA	30	30	21	42
SON	26	35	22	30
	Rain excess in NEA			
	La Niña	Warm SATL	Cold NATL	Without SST anomalies
DJF	22	22	33	58
MAM	39	36	43	21
JJA	26	43	35	26
SON	40	20	10	45

basin. A tendency toward an excess of rain is observed south of 10 °S when the southern Atlantic is cold (Figure 14). Specific SST-related rainfall anomalies are observed in eastern Ecuador: excess of rain during El Niño and deficit when the southern Atlantic is anomalously cold. Regional–global factors, such as SST variability, may interfere with the local and synoptic factors providing rainfall in the WA and SA.

The activity of extra-tropical perturbations, which is an important synoptic factor of rainfall variability in the southwestern Amazon and WA (Virji and Kousky, 1983; de Oliveira and Nobre, 1986; Ronchail, 1989; Garreaud and Wallace, 1998; Liebmann *et al*., 1999; Seluchi and Marengo, 2000) help explain the ENSO-related rainfall variability in these regions as it does in southeastern South America (SESA). In SESA, during El Niño (in spring and during the following winter), abnormally wet conditions have been explained by mid-latitude blocking in the southeastern Pacific combined with an intense subtropical jet that favoured the maintenance of persistent active frontal systems (Kousky *et al*., 1984; Aceituno, 1988). Cazes *et al*. (1996) associated the wet El Niño conditions with a northward shift of the extra-tropical cyclonic trajectories due to blocking in the southeastern Pacific. Dry conditions during La Niña are associated with inverse atmospheric conditions.

The SA and WA are at the boundary between SESA and the NEA, two regions where the ENSO signals are strong and inverse. Consequently, the El Niño-related signal in the southwestern Amazon and WA is weakly significant on an annual time scale, probably because the rainfall anomalies oscillate between an excess of rain associated with an intense frontal activity during the colder period of the year, as occurs in SESA, and a deficit of rain in summer at the core of the El Niño activity in the NA. During La Niña, weak activity of the extra-tropical perturbations could explain the deficit of rain in the SA, as is found in SESA. These results are consistent with those of Ronchail (1998) concerning the lowlands of Bolivia.

Rainfall in the SA is also dependent on the northwesterly flow (northerly trade winds deviated by the Andes) and on the moisture transport from the NATL, as hypothesized by Marengo (1992). Some evidence of that relationship is shown in our work. During warm NATL events, negative rainfall anomalies in the whole Amazon basin may be explained by negative pressure anomalies above the warm northern Atlantic waters and by the weak trade winds resulting in a lack of moisture advection. Moreover, in winter, the local lack or decrease of moisture, in particular in the southern basin, could explain why the warm NATL-related dryness is particularly important during this season. However, as seen earlier, the total amount of rainfall is very low in winter. A few raindrops can misleadingly exaggerate anomalies. In any event, this result is consistent with Molinier *et al*. (in press), who found a negative correlation between rainfall and NATL SST anomalies in the southwestern part of the Amazon basin. The upcoming studies of the meteorological community on the low-level jet to the east of the Andes should provide more elements about Atlantic SST-related meridional moisture transport in South America.

In the southwestern Amazon, an excess of rainfall is observed during cold events in the southern Atlantic, mainly in summer and spring. This is consistent with the fact that the 1990s floods in the Mamoré River (Bolivia) occurred simultaneously with cold SSTs in the southern Atlantic (Ronchail and Bourrel, 2001). Moreover, cold events in the southern Atlantic that do not combine with other oceanic events are associated with some significant excess of rain in the southeastern Amazon. This merits further investigation on tropospheric conditions (wind, geopotential height, etc.) that associate the SST variability over the southern Atlantic Ocean and rainfall variability in the SA, as has been done for the SESA region by Barros *et al*. (2000) and Robertson *et al*. (2000). For instance, excesses of rain in the southeastern Amazon basin (Figure 5(d)) have been associated with strong low-level westerly wind anomalies at a tropical latitude and with negative SST anomalies in the SATL and in the subtropical southwestern Atlantic, an area that is outside the oceanic domain that has been considered in the present work (Ronchail and Cochonneau, 2002). In addition, all the studies concerning the South American convergence zone and its variability (e.g. see Nogués-Peagle and Mo, 1997; Liebmann *et al*., 1999) are important steps toward the comprehension of rainfall structures that are associated with tropical SSTs and those that are not associated with tropical SSTs, as shown in the cluster analysis.

The relationship between the oceanic warm or cool events and the rainfall anomalies, especially for the northern Amazon area, has already been commented on. In our work we provide some additional results about the well-defined northeastern region of the Amazon basin, with emphasising on quantitative results, on seasonal aspects, and on the combined effects of SST anomalies. The different behaviours of the NEA basin and the other regions of the Amazon basin are commented on. The SST-related rainfall anomalies in the SA and WA are few, except in southeastern Amazon where the El Niño signal is strong. Otherwise, the weak signals that dominate often occur during the driest part of the year, so that they are hardly perceptible on the annual time scale.

As it is not possible to individualize certain oceanic signals during the 1977–99 period, further investigation covering a longer period and involving more oceanic events is needed. Further investigations that involve the tropical and extra-tropical atmosphere and ocean SSTs in the global ocean are needed to understand the rainfall variability in the SA and WA and that part of the rainfall variability in the NEA that is not associated with tropical SSTs.

ACKNOWLEDGEMENTS

Special thanks are given to Henri Laurent, Patricio Aceituno, and to other reviewers of this paper for their helpful comments.

NOTE

1. Agência Nacional de Energia Eléctrica (ANEEL); Institut de Recherche pour le Développement (IRD); Universidade de Brasilia (UnB).

REFERENCES

Aceituno P. 1988. On the functioning of the southern oscillation in the South American sector: surface climate. *Monthly Weather Review* **116**: 505–524.

Barros V, Gonzalez M, Liebmann B, Camilloni I. 2000. Influence of the South Atlantic convergence zone and South Atlantic surface temperature on interannual summer rainfall variability in southeastern South America. *Theoretical and Applied Climatology* **67**: 123–133.

Cazes G, Pisciottano G, Terra R. 1996. Climate variability in southeastern South America and anomalous circulation patterns during November: simulation with a AGCM. In: *Actas VII Congresso Latinoamericano e Iberico de Meteorologia*, Buenos Aires, Argentina; 335–336.

De Oliveira AS, Nobre CA. 1986. Interactions between frontal systems in South America and tropical convection over the Amazon. In: *Preprints, Second International Conference on Southern Hemisphere Meteorology, Wellington*. American Meteorological Society: Boston, MA; 56–59.

Enfield DB, Mayer A. 1997. Tropical Atlantic sea surface temperature variability and its relation to El Niño–southern oscillation. *Journal of Geophysical Research* **102**: 929–945.

Fielding AH. 2002. Cluster analysis: an online tutorial. http://asio.jde.aca.mmu.ac.uk/multivar/ca.htm. [Last accessed 6th September, 2002].

Figueroa SN, Nobre CA. 1990. Precipitation distribution over central and western tropical South America. *Climanálise* **6**: 36–40.

Fu R, Zhu B, Dickinson RE. 1999. How do atmosphere and land surface influence seasonal changes in the tropical Amazon? *Journal of Climate* **12**: 1306–1321.

Garreaud R, Wallace J. 1998. Summertime incursions of midlatitude air into subtropical and tropical South America. *Monthly Weather Review* **126**: 2713–2733.

Grimm AM, Ferraz SET, Gomes J. 1998. Precipitation anomalies in southern Brazil associated with El Niño and La Niña events. *Journal of Climate* **11**: 2863–2880.

Harzallah A, Rocha de Aragão J, Sadourny R. 1996. Interannual rainfall variability in northeast Brazil: observation and model simulation. *International Journal of Climatology* **16**: 861–878.

Hastenrath S. 2001. Upper air mechanisms of the southern oscillation in the tropical Atlantic sector. *Journal of Geophysical Research* **105**: 14 997–15 009.

Hastenrath S, Heller L. 1977. Dynamics of climatic hazards in northeast Brazil. *Quarterly Journal of the Royal Meteorological Society* **110**: 77–92.

Hiez G. 1977. L'homogénéité des données pluviométriques. *Cahiers ORSTOM, série Hydrologie* **14**: 129–172.

Hiez G, Cochonneau G, Séchet P, Fernandes UM. 1992. Application de la méthode du vecteur régional à l'analyse de la pluviométrie annuelle du bassin amazonien [Application of the regional vector method to the analysis of annual pluviometry of the Amazon basin]. *Veille Climatique Satellitaire* **43**: 39–52.

Horel JD, Hahmann AN, Geisler JE. 1989. An investigation of the annual cycle of convective activity over the tropical Americas. *Journal of Climate* **2**: 1388–1403.

Houghton RW, Tourre YM. 1992. Characteristics of low-frequency sea surface temperature fluctuations in the tropical Atlantic. *Journal of Climate* **5**: 765–771.

Kousky VE. 1988. Pentad outgoing longwave radiation climatology for the South American sector. *Revista Brasileira de Meteorologia* **3**: 217–231.

Kousky VE, Kayano MT, Cavalcanti IFA. 1984. A review of the southern oscillation: oceanic, atmospheric circulation changes and related rainfall anomalies. *Tellus A* **36**: 490–504.

Liebmann B, Marengo JA. 2001. Interannual variability of the rainy season and rainfall in the Brazilian Amazon basin. *Journal of Climate* **14**: 4308–4317.

Liebmann B, Kiladis G, Marengo J, Ambrizzi T, Glick J. 1999. Submonthly convective variability over South America and the South Atlantic convergence zone. *Journal of Climate* **12**: 1877–1891.

Marengo J. 1992. Interannual variability of surface climate in the Amazon basin. *International Journal of Climatology* **12**: 853–863.

Marengo J, Hastenrath S. 1993. Case studies of the extreme climatic events in the Amazon basin. *Journal of Climate* **6**: 617–627.

Marengo J, Nobre CA, Sampaio G. 1998. On the associations between hydrometeorological conditions in Amazonia and the extremes of the southern oscillation. *Bulletin de l'Institut Français d'Études Andines* **27**: 789–802.

Marengo J, Liebmann B, Kousky V, Filizola N, Wainer I. 2001. Onset and end of the rainy season in the Brazilian Amazon basin. *Journal of Climate* **14**: 833–852.

Molion LCB. 1987. Climatologia dinâmica da regiâo Amazonica: mecanismos de precipitaçao. *Revista Brasileira de Meteorologia* **2**: 107–117.

Molion LCB. 1993. Amazonian rainfall and its variability. In: *Hydrology and water Management in the Humid Tropics*. Cambridge University Press: Cambridge; 99–111.

Molinier M, Guyot JL, de Oliveira E, Guimarães V. 1996. Les régimes hydrologiques de l'Amazone et de ses affluents. In: *Hydrologie tropicale: geoscience et outil pour le développement*. *IAHS publication* **238**. IAHS: Paris; 209–222.

Molinier M, Ronchail J, Guyot JL, Cochonneau G, de Oliveira E, Guimarães V. In press. Hydrological variability in the Amazon drainage basin and African tropical basins. *Hydrological Processes*.

Montecinos A, Diaz A, Aceituno P. 2000. Seasonal diagnostic and predictability of rainfall in subtropical South America based on tropical Pacific SST. *Journal of Climate* **13**: 746–758.

Moron V, Bigot S, Roucou P. 1995. Rainfall variability in subequatorial America and Africa and relationships with the main sea-surface temperature modes (1951–1990). *International Journal of Climatology* **15**: 1297–1322.

Moura AD, Shukla J. 1981. On the dynamics of droughts in northeast Brazil: observations, theory and numerical experiments with a general circulation model. *Journal of the Atmospheric Sciences* **38**: 2653–2675.

Nobre P, Shukla J. 1996. Variations of sea-surface temperature, wind stress and rainfall over the tropical Atlantic and South America. *Journal of Climate* **9**: 2464–2479.

Nogués-Peagle J, Mo KC. 1997. Alternating wet and dry conditions over South America in summer. *Monthly Weather Review* **125**: 279–291.

Pezzi LP, Cavalcanti IFA. 2001. The relative importance of ENSO and the tropical Atlantic sea surface temperature anomalies for seasonal precipitations over South America: a numerical study. *Climate Dynamics* **17**: 205–212.

Rao V, Hada K. 1987. Characteristics of rainfall over Brazil: seasonal variations and connections with the southern oscillation. *INPE 4432-PRE/1234*, São José dos Campos, Brazil.

Robertson AW, Mechoso CR, Kim Y. 2000. The influence of Atlantic sea surface temperature anomalies on the North Atlantic oscillation. *Journal of Climate* **13**: 122–138.

Rogers JC. 1988. Precipitation variability over the Caribbean and tropical Americas associated with the southern oscillation. *Journal of Climate* **1**: 172–182.

Ronchail J. 1989. Advecciones polares en Bolivia: caracterizacion de los effectos climaticos. *Bulletin de l'Institut Français d'Etudes Andines* **18**: 65–73.

Ronchail J. 1997. Interdecadal variability of rainfall in Bolivia and sea-surface temperatures. In: *Preprints for the Fifth International Conference on Southern Hemisphere Meteorology and Oceanography,7–12 April, Pretoria, South Africa*. American Meteorological Society: Boston, MA.

Ronchail J. 1998. Variabilité pluviométrique en Bolivie lors des phases extrêmes de l'Oscillation Australe du Pacifique (1950–1993). *Bulletin de l'Institut Fançais d' Etudes Andines* **27**: 687–698.

Ronchail J, Bourrel L. 2001. Enchentes, chuvas e circulação atmosférica na bacia amazônica boliviana. In: *Communication to Congremet VIII–Climet IX*, 7–11 May, Buenos-Aires.

Ronchail J, Cochonneau G. 2002. Main patterns of summer rainfall variability and associated circulation in western and southern Amazon. In: *Communication to the VAMOS/CLIVAR Conference on South American Low-level Jet*, *Santa Cruz de la Sierra, Bolivia, 5–7 February.*

Roucou P. 1997. Impact des températures de surface océanique d'échelle globale sur la dynamique de l'atmosphère et les précipitations tropicales en Amérique du Sud à l'est des Andes: diagnostic et simulation numérique. *Thesis of the Centre de Recherche de Climatologie, ESA5080 CNRS/Université de Bourgogne*, France.

Seluchi M, Marengo J. 2000. Tropical–midlatitude exchange of air masses during summer and winter in South America: climatic aspects and examples of intense events. *International Journal of Climatology* **20**: 1167–1190.

Trenberth KE. 1997. The definition of El Niño. *Bulletin of the American Meteorological Society* **78**: 2771–2777.

Uvo CB, Repelli CA, Zebiak SE, Kushnir Y. 1998. The relationships between tropical Pacific and Atlantic SST and northeast Brazil monthly precipitation. *Journal of Climate* **11**: 551–562.

Virji H, Kousky VE. 1983. Regional and global aspects of low latitude frontal penetration in Amazonas and associated tropical activity. In: *Preprints, First International Conference on Southern Hemisphere Meteorology, São José dos Campos*. American Meteorological Society: Boston, MA; 215–220.

Vuille M, Bradley RS, Keimig F. 2000. Climate variability in the Andes of Ecuador and its relation to tropical Pacific and Atlantic sea surface temperature anomalies. *Journal of Climate* **13**: 2520–2535.

Wilks DS. 1995. *Statistical Methods in the Atmospheric Sciences*. Academic Press: San Diego.

