HYDROLOGICAL PROCESSES
Hydrol. Process. (2009)
DOI: 10.1002/hyp.7396

Long-term trends and cycles in the hydrometeorology of the Amazon basin since the late 1920s

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Abstract:

Rainfall and river indices for both the northern and southern Amazon were used to identify and explore long-term climate variability on the region. From a statistical analysis of the hydrometeorological series, it is concluded that no systematic unidirectional long-term trends towards drier or wetter conditions have been identified since the 1920s. The rainfall and river series showing variability at inter-annual scales linked to El Niño Southern Oscillation was detected in rainfall in the northern Amazon. It has a low-frequency variability with a peak at −30 years identified in both rainfall and river series in the Amazon. The presence of cycles rather than a trend is characteristic of rainfall in the Amazon. These cycles are real indicators of decadal and multi-decadal variations in hydrology for both sides of the basin. Sea-level pressure (SLP) gradients between tropics and sub topics were explored in order to explain variability in the hydrometeorology of the basin. Sea surface temperature (SST) gradients inside the tropical Atlantic and between the tropical Atlantic and the sub-tropical Atlantic have been assessed in the context of changes in rainfall in the Amazon, as compared to northern Argentina. Trends in SSTs in the subtropical Atlantic are linked to changes in rainfall and circulation in northern Argentina, and they seem to be related to multi-decadal variations of rainfall in the Amazon. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS climate trends; decadal variability; Amazon; rainfall

Accepted 1 October 2008

INTRODUCTION

Studies of long-term climate change and climate trends in South America have been hampered by the scarcity of climatic and hydrological data. This is even more pronounced in the Amazon region. Evidence for climate fluctuations in the Amazon on decade-to-century time scales have shown a tendency to be biased towards higher frequencies that are related to regional climate processes such as the Southern Oscillation. The Amazon basin has experienced increased changes in land use over time, and its possible consequences in regional and global climate have motivated a host of model experiments (Zeng *et al.*, 1996; Marengo and Nobre, 2001; Marengo *et al.*, 2008 and references quoted in). So far, no signs of any long-term systematic tendency have been detected in rainfall or river records in the basin.

A few observational studies have documented changes in climate for the basin: Victoria *et al.* (1998) have documented a tendency for an increase in air temperatures since the beginning of the century in several cities in the Amazon region, which they attribute to global warming. Gentry and Lopez-Parodi, 1980; Rocha *et al.*, 1989; Chu *et al.*, 1994; Dias de Paiva and Clarke, 1995; Marengo 1995; Guyot *et al.*, 1998; Marengo *et al.*, 1998, 2008; Marengo 2004 have analysed trends in rainfall and discharges in the Amazon River and its tributaries. Trends differ depending on the length of the times series used. On the other hand, proxy-climate indicators such as lake sediments, fossilized pollen, and tree rings have identified (1) Mega-El Niños in the past (Meggers, 1994), (2) relatively cooler conditions in the Amazon basin 10 000 years before the present [see reviews in Marengo and Rogers (2001)] and (3) Increased rainfall in subtropical South America and possibly the southern Amazon due to regional changes in the meridian circulation and moisture transport between tropics and subtropics (Villalba *et al.*, 1998).

Long-term variations in moisture transport from the North Atlantic have been studied by Costa and Foley (1999), Curtis and Hastenrath (1999) and Marengo *et al.* (2004) in the Amazon basin, and they are related to possible changes in sea surface temperature (SST) meridian sea-level pressure (SLP) gradients in the tropical Atlantic. They used the NCEP global reanalyses (Kalnay *et al.*, 1996). With the availability of global reanalysis, studies on the variability of water balance, moisture transport and moisture divergence have been implemented for the region, but some of these studies have been difficult to validate due to the lack of sound observations. There is therefore a need for observational studies, which in turn will be used for validating studies using reanalyses and for identifying climate change signals in the basin.

Several studies have been devoted to documenting decadal and multi-decadal scale variability in the hydrometeorology of the Atlantic sector (Nobre and Shukla, 1996; Venegas *et al.*, 1996, 1998; Wagner, 1996; Marengo *et al.*, 1998; Curtis and Hastenrath, 1999; Costa and Foley, 1999; Rao *et al.*, 1999; Zhou and Lau, 2001; Marengo 2004). Some of these studies identify a shift in the Atlantic ITCZ that has led to increased rainfall

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in northeast Brazil (Hastenrath and Greischar, 1993) and possible in the Amazon (Wagner, 1996; Curtis and Hastenrath, 1999). In comparison, for the adjacent La Plata-Parana River basin, changes in SST and meridian SLP gradients may be responsible for decadal-scale circulation changes leading to a systematic increase in rainfall and river levels in subtropical South America (Venegas *et al.*, 1996, 1998; Garcia and Vargas, 1998; Genta *et al.*, 1998; Robertson and Mechoso, 1998; Villalba *et al.*, 1998; Barros *et al.*, 2002; Trenberth *et al.*, 2007; Magrin *et al.*, 2007 and references quoted in). Recent work by Obregon and Nobre (2003) had identified shifts in the rainfall regime in the mid-1970s for northwestern Amazonia and southern Brazil, with positive and significant trends since 1973 for southern Brazil, and with negative and significant trends since 1975 for northwestern Amazonia.

Chen *et al.* (2001) have used the 1958–1998 NCEP reanalyses. Their results suggest that changes in the global-scale divergent circulation during the last 40 years have favoured a humidification of the Amazon basin and, thus, an increase in the width of the precipitation basin by approximately 20%. Similar results were found by several other authors for both the Amazon and northeast Brazil, using the NCEP and NASA-GEOS reanalyses data sets beginning from the late 1950s (Wagner, 1996; Curtis and Hastenrath, 1999; Hastenrath, 2001; Zhou and Lau, 2001 among others).

More recently, an analysis of decadal and long-term patterns of rainfall has been carried out using a combination of rain-gauge and gridded rainfall data sets, for the entire Amazon basin and for its northern and southern sub basins (Marengo, 2004). This study covers 1929–1998, but more detailed analyses were performed during 1950–1998 regarding rainfall variability and variations in circulation and sea surface temperature fields. Negative rainfall trends were identified for the entire Amazonia, while at regional levels there was a negative trend in northern Amazonia and a positive trend in southern Amazonia. Perhaps, the most important aspects of this work is the identification of decadal time-scale variations in rainfall in Amazonia, with periods of relatively drier and wetter conditions, which are contrasting for northern and southern Amazonia. Spectral analyses show decadal time scale variations in southern Amazonia, while northern Amazonia exhibits both inter-annual and decadal-scale variations. Shifts on the rainfall regime in both sections of the Amazon basin were identified in mid-1940s and -1970s. After 1975–1976, northern Amazonia exhibited less rainfall than before 1975. Changes in the circulation and oceanic fields after 1975 suggest an important role of the warming of the tropical central and eastern Pacific on the decreasing rainfall in northern Amazonia, owing to more frequent/intense strong El Niño events during the relatively dry period of 1975–1998.

Ronchail *et al.* (2002) have suggested that these excesses occur more during wintertime, and therefore rainfall anomalies in southern Amazonia could be attributed to the enhancement of the activity of extratropical perturbations during some El Niño years, and the ENSO-related rainfall anomalies in this region are partly similar to those described in southeast South America (Liebmann *et al.*, 1999; Grimm *et al.*, 2003; Seluchi and Marengo 2000).

Work in progress demonstrates the indicators of decadal and multi-decadal climate variability in the entire Amazon. Sub basins show some association with modes of variability typical of the subtropical Pacific and Atlantic Oceans, such as the North Atlantic and Pacific Decadal Oscillations. Stronger correlations of opposite signs between those oscillations and rainfall in both the northern and southern Amazon have been found for long-term time scales.

In this paper, we use the hydrometeorological indices for the Amazon basin and its sub basins defined by Marengo (2004) to explore long-term variability of climate since the late 1920s and the presence of trends and/or cycles in rainfall and river indices in the basin. We also explain connections between this variability and large-scale SST and SLP gradients within the tropical region or between tropics–subtropics that may induce changes in atmospheric circulation and rainfall in the region. We suggest that these long-term changes in SST and SLP gradients in the tropical and subtropical Atlantic sector (that includes South America east of the Andes and the Atlantic Ocean) lead to changes in moisture transport, and thus to rainfall.

OBJECTIVES, DATA AND METHODOLOGY

The main objective of this study is the assessment of long-term trends and cycles in precipitation in the entire Amazon basin, and over the northern and southern sections. It was addressed by analysing rainfall and streamflow indices, dating from the late 1920s, for both the northern and southern Amazon. Links between long-term rainfall variability and changes in regional circulation (expressed as SLP gradients) and SST regimes in the Atlantic sector, either within the tropical region both sides of the equator or between tropics and mid-latitudes, were explored.

We used the northern Amazonian rainfall (NAR) and southern Amazonian rainfall (SAR) rainfall initially developed by Marengo (1992), Marengo and Hastenrath (1993) and updated by Marengo (2004). Figure 1a and b shows the stations used in this study and the domains of the NAR and SAR regions. These indices represent regional aspects of rainfall in the basin and were constructed to represent rainfall regimes in the northern and southern sections of the basin. These and their domains and the rainfall stations used from each region are shown in Figure1a and b. NAR's domain includes northern and central Amazonia, including the mouth of the Amazon River, and shows the season of maximum rainfall in March–April. SAR's domain includes the southern part of the basin, and these regions shows the peak of the rainy season in January–April and a pronounced minimum rainfall during June–August. In both series, observed rainfall totals were seasonalized from September to August, and then mean and standard deviation were calculated. The new NAR and SAR indices include now 78 and 86 stations respectively. Sources of rainfall data are the Brazilian National Agency for Water Resources ANEEL, the Brazilian Meteorological Service INMET, and CPTEC. See Marengo (2004) for more details on the NAR and SAR indices.

The Amazon River series at Obidos was used for this study. Additional river series are the Xingu River at Belomonte, the Tocantins River at Tucurui (this river is outside the domain of the Amazon basin), the Jamari River at Samuel, the Curua-Una River at Curua-Una and the Uatuma River at Balbina. River data were provided by PORTOBRAS, ELETROBRAS e ELETRONORTE, from Brazil. Please refer to Marengo *et al.* (1998) for locations of the stations and for the trend analysis in rainfall series and its significance, as assessed using the Mann–Kendall test.

The Southern Oscillation Index (SOI), defined as the difference of mean sea-level pressure between Tahiti and Darwin, was used here as an indicator of El Niño. An index of the SST representative of the South Atlantic Ocean has been derived for a box (12–26 °S) from 1950 to 1998 during December–February, similar to Venegas *et al.* (1996). Indices of mean SLP were derived on the basis of the long-term reliable pressure records for the interior of tropical and subtropical South America (Villalba *et al.*, 1998). Pressure records in Quixeramobim (5 °S), Cuiaba (15 °S) and Reconquista (29 °S) were used to estimate meridian SLP gradients between tropical and subtropical regions. The pressure difference was normalized by the standard deviation. Pressure data were available dating from the beginning of the century, but the time span of 1929 until 1994 was used as SLP data were also available. They were provided by R. Villalba from IANIGLA (Mendoza, Argentina) and P. Jones from the University of East Anglia/CRU (Norwich, UK).

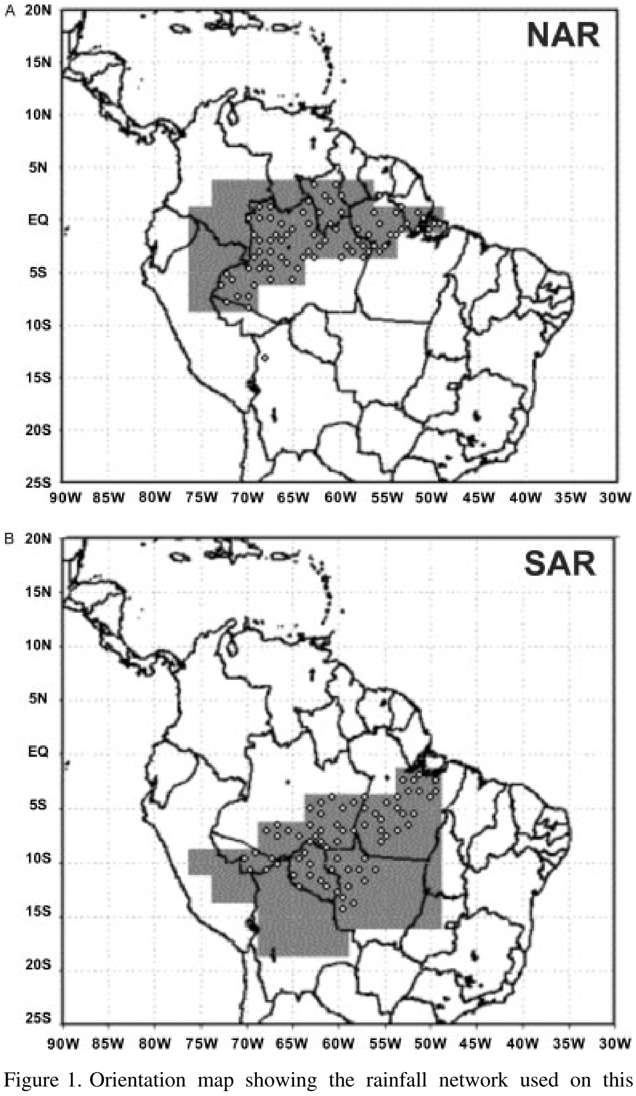

Figure 1. Orientation map showing the rainfall network used on this study for northern Amazonia (a) and southern Amazonia (b). (Source: Marengo, 2004)

RESULTS

Long-term variations in hydrometeorological records in the Amazon beginning in the late 1920s

The analysis of the annual rainfall time series in the Amazon represented by the NAR and SAR indices (Figure 2a, b) indicates slight negative trends for the northern Amazon and positive trends for the southern Amazon. However, they are weak and significant at 5% only in the southern Amazon. On inter-annual time scales, rainfall in the northern Amazon shows some association with the extremes of the Southern Oscillation, such as the large negative rainfall anomalies during the El Niño events of 1983, 1987 and 1998 (Figure 2d), which are reflected in reduced rainfall over the northern Amazon basin. However, the SO variability accounts for less than 45% of the rainfall variance in the northern Amazon. El Niño does not appear to have any significant impact on the southern Amazon rainfall. A good example of this is the drought of Amazonia in 2005, which, together with the drought of 1963–1964, occurred during non El Nino years (Marengo *et al.*, 2008).

More important than the trends themselves are the succession of relatively wet and dry periods (cycles) of approximately 20–30 years, suggesting indicators of long-term variability on multi-decadal time scales. The period 1945–1976 was regionally wet in the northern Amazon, whereas from 1977 onwards there has been a tendency for relatively drier conditions. This was also observed for the period from 1929 until the beginning of the 1940s. The observed climate shift in the Pacific sector in 1975–1976 (Trenberth, 1990; Trenberth and Hurrel, 1994; Zhang *et al.*, 1997) seems to have affected the northern and southern Amazon, in opposite ways, by changing rainfall regimes in both regions towards relatively drier/wetter conditions. In comparison, rainfall in northeast Brazil shows a slightly positive trend since 1950, as well as a decadal scale variability linked to tropical Atlantic variability (Hastenrath and Greischar 1993; Nobre and Shukla 1996; Hastenrath 2001). A new

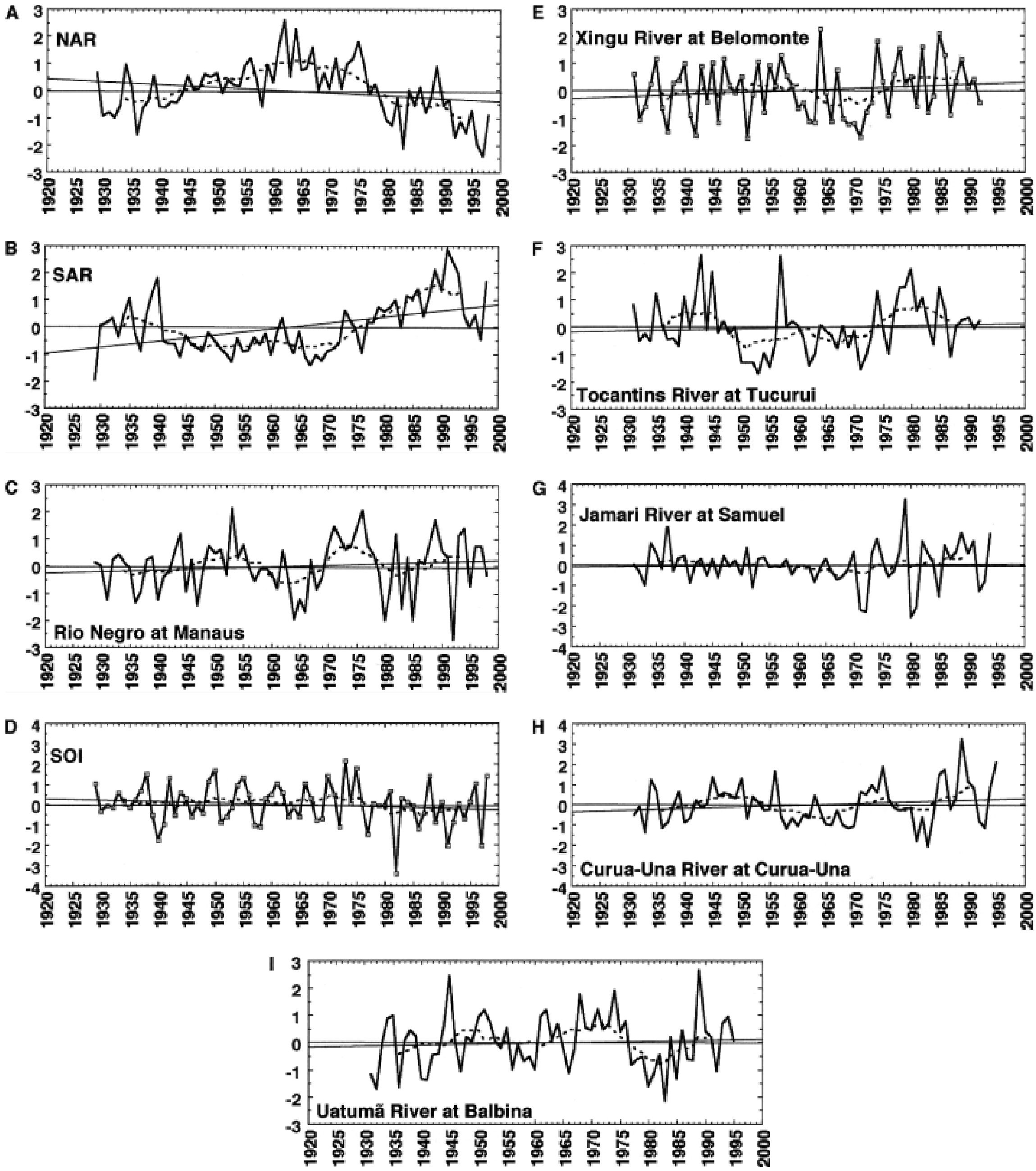

Figure 2. Hydrometeorological indices for the Amazon basin. They are expressed as anomalies normalized by the standard deviation from the long-term mean, (a) NAR, (b) SAR, (c) Rio Negro at Manaus, (d) SOI, (e) Xingu River at Belomonte, (f) Tocantins River at Tucurui, (g) Jamari River at Samuel, (h) Curua-Una River at Curua-Una, (i) Uatuma River at Balbina and (j) Amazon River at Obidos. The thin line represents the trend. The broken line in (a–(i) represents the 10-year moving average. (a) and (b) are for September–August; (c), (e)–(j) is for the hydrological year September–August, and (d) SOI is for January–February

shift may have occurred by the end of the twentieth century (Marengo, 2004).

Chen *et al.* (2001, 2003) identified an increase in rainfall since the 1978/1998 period as compared to the 1958/1977 period, and linked this tendency to interdecadal variations in the global divergent circulation before and after 1977. Their analysis shows an intensification of the near-surface branch of the Walker cell, suggesting an increase in low-level moisture convergence over the basin. This is consistent with increasing rainfall trends in the basin during the period 1978–1998 as compared to those in 1959–1977. Their conclusions do not seem to agree with our findings, and this may be due to the fact that Chen's analyses took into consideration the whole Amazon basin, while we examined the northern and southern regions separately.

The upward trends in rainfall and stream-flow from the early 1960s until the mid-1970s in the Amazon, identified by Gentry and Lopez-Parodi (1980), are consistent with the 'positive cycle' of the NAR from 1953 to 1977. Similar tendencies were found for the Rio Negro in Manaus and the Solimoes River at Manacapuru (Guyot *et al.*, 1998). The SAR index (Figure 2b) shows a tendency for an anomalous dry period extending from the mid-1930s until the mid-1970s, while anomalously wet periods are observed especially from 1977 until the present. The southern Amazon experiences a long-term variability that differs from that of the northern Amazon.

The Rio Negro levels (Figure 2c) exhibit a positive trend significant at a 5% level, consistent with similar positive trends in the Uatuma and Curua-Una Rivers in the northern Amazon (Figure 2h, i). The water levels of the Rio Negro in Manaus represent a mixing of patterns of variability in the Amazon Rivers, which extends along both sides of the equator. The signals of El Niño could be offset by the non-El Nino variability of rainfall on the southern part of the western Amazon. This was also observed by Guyot *et al.* (1998) by analysing the water levels of the Solimões River in the western Amazon. However, water levels below normal were detected during the strongest El Nino years of 1983 and 1998. Long-term trends are not so evident, as in the other small rivers with basins located entirely in the northern or southern Amazon.

Discharges above normal during the second half of the 1940s and the late 1960s to mid-1970s and lower discharges during the first half of the 1980s are consistent with the variability of rainfall in the northern Amazon (Figure 2a). In the southern Amazon, the variability of SAR resembles that of the discharges of the Jamari River at Samuel (Figure 2g), and, to a lesser degree, the Xingu River (Figure 2e). The positive significant trends of SAR are consistent with the positive trends (significant at 10% level) of the Jamari and Xingu River annual series. The Tocantins River series also exhibits weak positive trends. Over the long term, based on 1970–1998 time series data, the discharges of the Amazon River at Obidos (Figure 2j) exhibit a slightly negative trend. This is attributed to the occurrence of more frequent strong El Niño events during that period (Marengo *et al.*, 1998; Guyot *et al.*, 1998). Upward trends occurring in the period 1951–1977 and downward trends occurring in the period 1976–98 were observed in the Uatuma River levels at Balbina, located in the northern Amazon, and in rainfall in the northern Amazon (Figure 2a, i). These trends are less evident for Rio Negro levels at Manaus (Figure 2c).

Trends in rainfall and river series in the Amazon

From the analysis of Figure 2, it is clear that there have been multi-decadal time-scale variations along the 1929–1998 period in the rainfall and river time series, such as the relatively wet period from the late 1950s to the mid-1970s in the northern Amazon, and the relatively dry period afterwards. Figure 3 depicts the annual cycle of rainfall in northern, southern and the entire Amazon for 3 years representative of the relatively wetter or drier periods exhibited in Figure 2. The northern Amazon (Figure 3a) and the southern Amazon (Figure 3b) show the most pronounced trends in rainfall, occurring during the peak of the rainy season between February–May (north) and January–April (south). An upward trend is apparent during 1979, particularly during the rainy season. In May–August, no trend is apparent for the southern Amazon. Studies by Chen *et al.* (2003) show that rainfall derived from the Global Historical Climatology Network GHCN data set exhibits inter-decadal variations and a positive trend since the mid-1950s to the late 1990s.

River discharge series in the basin were divided into different epochs: 1928–1950, 1951–1977 and 1978–1992, based on the analysis of Figures 2 and 3. For the rivers located in the northern Amazon (Figure 4a, b), the 1951–1977 epoch exhibits a substantial upward trend during the peak season, while a downward trend is detected during the recent 1976–1998 epoch. This recent epoch is characterized by more frequent and strong El Niño events (1982/1983, 1986/1987 and 1991/1994). No trends are apparent after September. For rivers in the southern Amazon and to the east of the Amazon (Figure 4c, d), trends are apparent as compared to

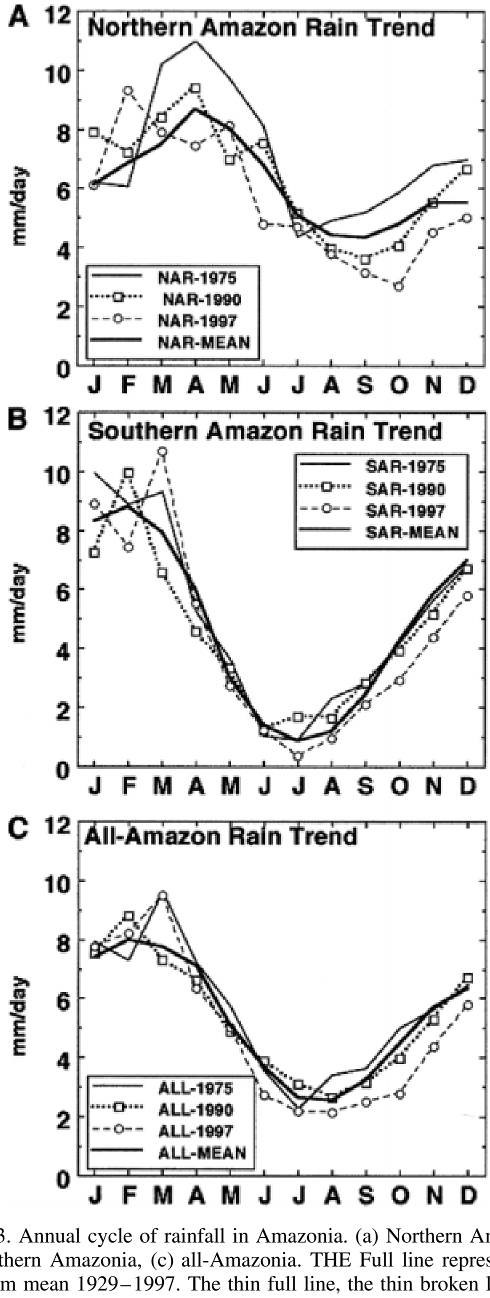

Figure 3. Annual cycle of rainfall in Amazonia. (a) Northern Amazonia, (b) Southern Amazonia, (c) all-Amazonia. THE Full line represents the long-term mean 1929–1997. The thin full line, the thin broken line with circles, and the thin line with squares are for years representative of several epochs from the decadal and multi-decadal variability

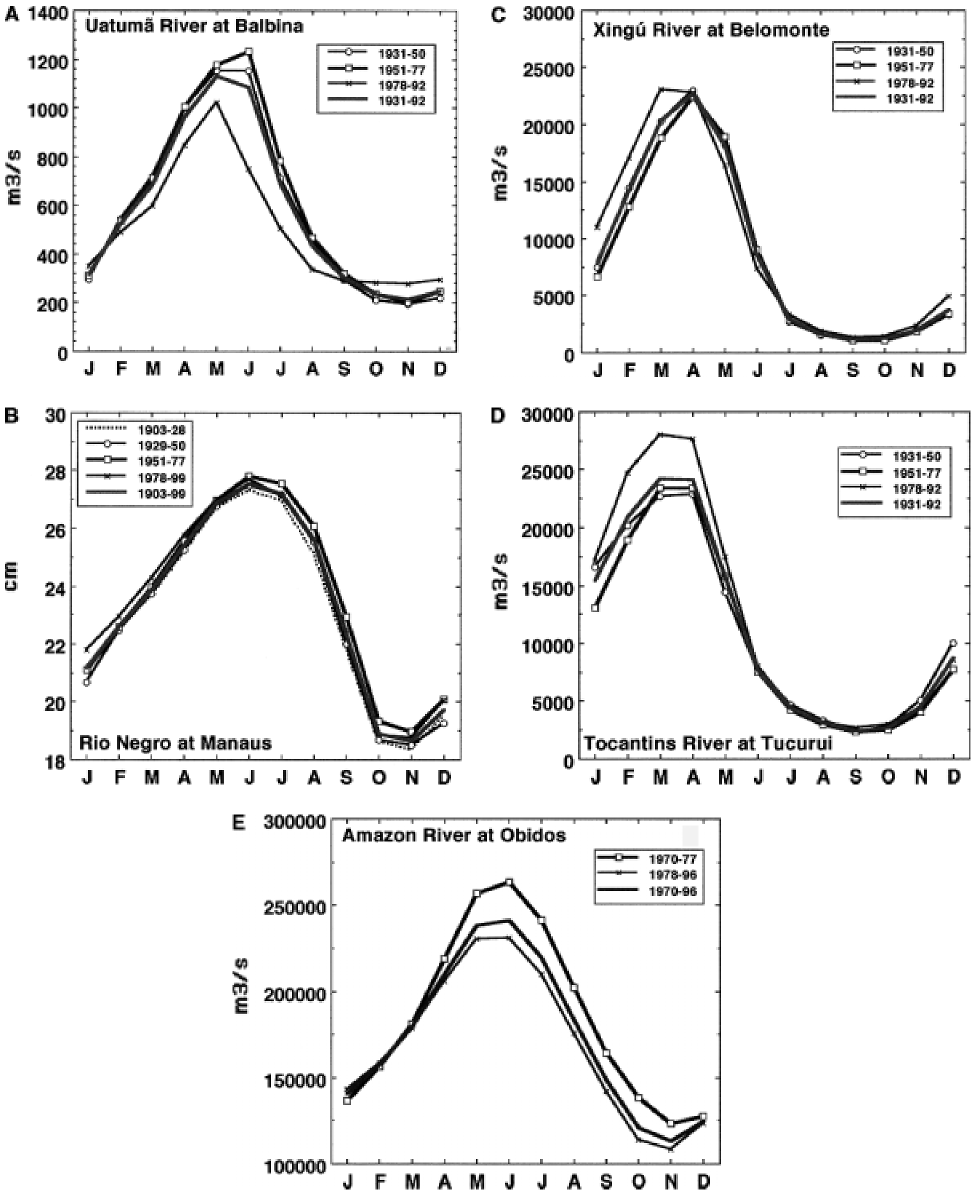

Figure 4. Annual cycle of river levels/discharges in Amazonia. (a) Uautuma River at Balbina, (b) Rio Negro at Manaus, (c) Xingu River at Belomonte, (d) Tocantins River at Tucurui, (e) Amazon River at Obidos. Different lines indicated on the upper right of left sides of each panel represent the long-term mean, as well as the means of the periods that include 1951–1977, 1978–1992 and after 1992. The lines were plotted according to the availability of data

the northern Amazon. The latest epoch of 1978–1992 exhibits greater discharges than for the previous epochs. Discharges of the Xingu River (Figure 4c) show a slight positive trend during the 1978–1992 period and a weak negative trend for the 1951–1977 period, both occurring in early summer. This shows that rivers in the northern and southern Amazon do not share the same variability. The Tocantins River discharge (Figure 4d) is outside the domain of the Amazon basin. It exhibits an upward trend during the 1978–1992 epoch, which is due to an anomalously wet period around 1984–1986, as detected in the rainfall series and other rivers in the region by Marengo *et al.* (1998) and Uvo *et al.* (1998). This was not noted in the Amazon basin. The Obidos records (Figure 4e) exhibit an upward trend during the 1970–1977 epoch between May and December, becoming more significant during the May–August peak season. The downward trends during the 1978–1996 epoch is consistent with the reported association between low discharges at Obidos and El Niño (Guyot *et al.*, 1998; Marengo *et al.*, 1998) because this epoch exhibited three strong and extended El Niño events.

On the basis of the analysis of rainfall and river series and the length of the climate and hydrology series, the magnitude and direction of trends suggest that, over the long term, the northern Amazon shows modest negative rainfall trends, even though it is uncertain if this indicates a tendency towards relatively drier conditions in the basin. Stronger and more frequent El Niño events reported over the last 25 years may have played a role in the weak negative trends found in the northern Amazon. If the years of El Niño events are removed from the analysis, rainfall in the northern Amazon shows modest positive trends. This, coupled with a systematic rainfall

DOI: 10.1002/hyp

increase in the southern Amazon, leads to the conclusion that there is a slight tendency for increasing rainfall in the basin, especially for the southern part of the basin. In general, significant trends towards wetter or drier conditions cannot be identified for the Amazon basin, at least for the period between the late 1920s and the mid-1990s. The most striking fact is that periods of relatively wetter or drier conditions in both the northern and southern Amazon have been detected as being of more importance than the trends themselves. These periods, lasting 20–30 years, are proof of multi-decadal variations in rainfall in the basin. They are similar to trends detected in rainfall in north-eastern Brazil, and seem to be related to the Pacific Decadal Oscillation (PDO) (Zhang *et al.*, 1997)

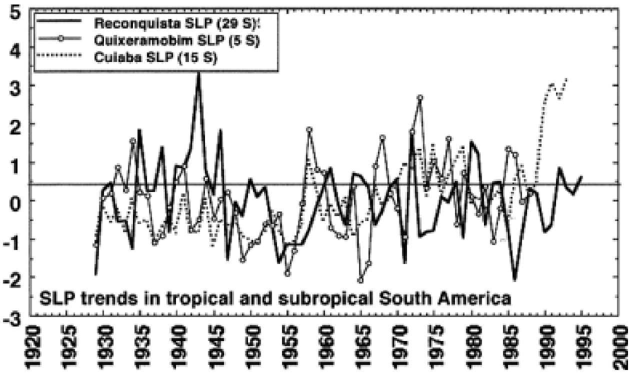

Figure 5. Annual SLP values in Quixeramobim (5S), Reconquista (29 S) and Cuiaba (15 S). Indices are expressed as the normalized departures from the long-term mean

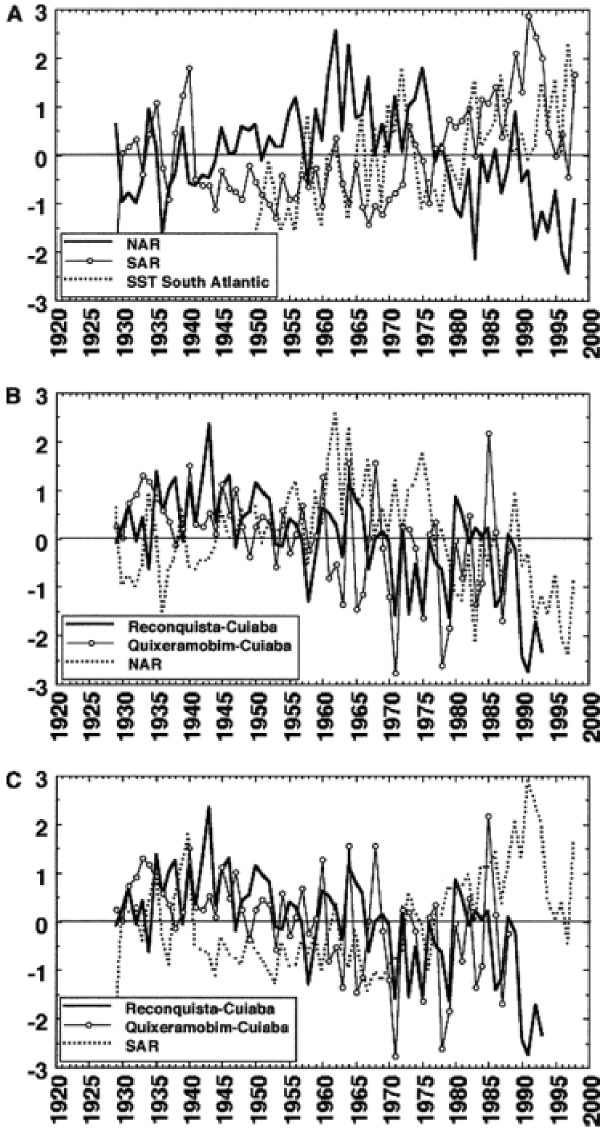

Figure 6. Annual SLP gradients, SST, and river indices. (a) NAR, SAR, SST subtropical South Atlantic; (b) NAR, SLP gradients Reconquista-Cuiaba and Quixeramobim-Cuiaba and (c) SAR, Reconquista-Cuiaba, Quixeramobim-Cuiaba. Indices are represented as the normalized departures from the long-term mean

Physical mechanisms related to trends in the Amazon and comparisons with observed trends in other regions in South America

The relatively modest long-term changes in rainfall and river discharges described above for the Amazon contrast with trends documented for regions such as north-eastern Brazil, and especially with the strong positive trends in river/rainfall series in the Parana River basin in southern Brazil-northern Argentina. The study by Obregon and Nobre (2003) shows that, for one representative station in northern Amazonia and other in southern Brazil, each region for the month with the peak season, the trends of rainfall in northern Amazonia show a negative trend and the trends in southern Brazil show a positive trend, with a shift in the rainfall regime in 1975 in both regions. Furthermore, their conclusions for southern Brazil seem to be applicable also to southern Amazonia, and to the Paraná River.

The observed increments in rainfall in subtropical South America have been related to changes in the sea-level pressure gradient between tropical and subtropical South America since 1950 (Villalba *et al.*, 1998). This, together with an observed increase of air temperature in subtropical South America and SSTs located in the subtropical South Atlantic (Venegas *et al.*, 1996, 1998), could have resulted in a latitudinal southward migration of the low pressure centre over South America as well as changes in the intensity and position of the subtropical Atlantic high.

Figures 5 and 6 show time series of NAR, SAR and indices of SST and meridian SLP gradients between tropics and subtropics and in between subtropics in the Atlantic sector. The differences in meridian SLP gradients reflect the transport of wet-air masses that produce rain. Tendencies in these SLP gradients also indicate changes in rain for the region. The SLP trends in near equatorial, tropical and subtropical regions shown in Figure 5 indicate systematic increases in the tropical SLP since 1950 (deduced from Cuiaba), while in the subtropics SLP declined gradually from the 1940s to the 1970s and remained below the normal during most of the years until 1993 (from the Reconquista records). Near the equator (from the Quixeramobim records), a general positive trend in SLP is also observed, consistent with Wagner (1996). In all the stations, a gradual increase in SLP since about 1950 is common. Low SLP values have been detected in those three places from the mid-1970s until the late 1990s.

Variations in rainfall in the northern and southern Amazon in response to changes in SLP meridian gradients are shown in Figure 6. Reconquista-Cuiaba (R-C) and Quixeramobim-Cuiaba (Q-C) SLP gradients are calculated, and then plotted against the NAR and SAR indices (Figure 6a, b). Correlation coefficients between SLP gradients and NAR are low or do not reach statistical significance at a 90% level. Both R-C and Q-C gradients exhibit negative trends since the late 1940s, consistent with a negative rainfall trend in the northern Amazon for the same period (Figure 6a). Since the mid-1950s, both gradients have decreased, reaching the lowest values during the 1970s and between the mid-1980s and early 1990s. Regarding long-term variations in the southern Amazon rain and SLP gradients (Figure 6b), the consistency between SLP gradients and rainfall is somewhat similar to the relationships between SLP gradients and the increased rainfall in subtropical South America as reported by Villalba *et al.* (1998). Increases/decreases in precipitation in northern Amazonia are characterized by a negative/positive meridian Q-C SLP gradient, indicating that northern Amazonian rainfall diminishes when the gradient is negative, while the opposite is detected for rainfall in southern Amazon. In this section of the basin, rainfall variations depend more on the tropic–subtropic (R-C) SLP gradient.

It is suggested that rainfall in the southern Amazon is mainly related to a strong advection of moist air from the northern section of the basin, with the northern Amazon acting like a source and the southern part acting as a sink of moisture to produce rain. The connection between both sections can be ascribed to circulation mechanisms that are more intense in the austral summer, responsible for the meridian exchange of air masses, not only between tropics-subtropics but also inside the tropical region. One of such features is the 'low-level jet' east of the Andes (Seluchi and Marengo, 2000; Marengo *et al.*, 2002, 2004) that acts as a moisture corridor and transports moisture from the Amazon into southern Brazil–Northern Argentina.

DISCUSSIONS AND CONCLUSIONS

Hydrometeorological indices for both the northern and southern Amazon since the late 1920s were implemented in order to study long-term variations and trends or tendencies. Associations with changes in regional circulation and surface oceanic conditions in the Atlantic sector were assessed in order to explore the possible causes of these variations. Meridian SLP and SST gradients in the Atlantic sector were analysed in order to explain the observed variations in rainfall in the Amazon, as well as comparisons made with observed long-term variations in adjacent regions, such as north-eastern Brazil and northern Argentina.

In this study, long-term variations and trends in the hydrometeorology of the Amazon basin are observed. Since 1929, long-term tendencies and trends, some of them statistically significant, have been detected in a set of regional-average rainfall time series in the Amazon basin and supported by the analysis of some river streamflow time series. These long-term variations are more characteristic of decadal and multi-decadal modes, indicators of natural climate variability (as the PDO), rather than any unidirectional trend towards drier conditions(as one would expect, due to increased deforestation or to global warming).

Northern and southern Amazonian regions exhibit low-frequency variability that is not in phase. An analysis of the hydrometeorological time series indicates that inter-annual cycles are stronger in the northern Amazon. On the other hand, decadal and multi-decadal variations are more evident in the southern Amazon. These decadal scale variations are linked to the variability of surface circulation over both the continent and the ocean, as explained by the consistency between rainfall and meridian SLP gradients to the east of the Andes, and the SST gradients over the Atlantic, both between near equatorial–tropical and tropical–subtropical latitudes. Even though these associations are not so strong as to explain the systematic increment in rainfall in subtropical South America, they still show that the Amazon basin does not vary uniformly across the basin, and that both sections seem to be linked with the northern section being a source of moisture for the southern basin. Therefore, particular regions of the basin have their own response to El Niño at inter-annual scales, and at inter-decadal scales there is a teleconnection between the north Pacific climate shift and the long-term rainfall variability all across the Amazon basin.

Systematic changes in SLP gradients between tropics–subtropics and the SSTs in the tropical Atlantic sector can be explained by changes in the strength of the subtropical high, together with associated surface wind. Changes seem to be dynamically linked to the observed upward trends in SSTs in the southern Atlantic. This reinforces the importance of the atmospheric forcing on a decadal time scale. These findings are consistent with other studies of the low-frequency changes in rainfall/river series in southern and central Brazil, Argentina, Uruguay and the West Coast of the Americas, and may be indicators of the modulation of the tropical hydrological cycles on large-scale atmospheric forcing. These decadal changes in climate are more due to natural climate variability rather than due to anthropogenic effects owing to land use changes.

ACKNOWLEDGEMENTS

We would like to thank Ricardo Villalba from Argentina for providing sea level pressure data. The author was partially funded by the Brazilian Research Council CNPq, the GEOMA Program and the UK Global Opportunity Fund-GOF-Dangerous Climate Change (DCC).

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