The drought of 2010 in the context of historical droughts in the Amazon region

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Abstract:

The year 2010 featured a widespread drought in the Amazon rain forest, which was more severe than the "once-in-a-century" drought of 2005. Water levels of major Amazon tributaries fell drastically to unprecedented low values, and isolated the floodplain population whose transportation depends upon on local streams which completely dried up. The drought of 2010 in Amazonia started in early austral summer during El Niño and then was intensified as a consequence of the warming of the tropical North Atlantic. An observed tendency for an increase in dry and very dry events, particularly in southern Amazonia during the dry season, is concomitant with an increase in the length of the dry season. Our results suggest that it is by means of a longer dry season that warming in the tropical North Atlantic affects the hydrology of the Amazon rivers at the end of the recession period (austral spring). This process is, sometimes, further aggravated by deficient rainfall in the previous wet season.

Index Terms. Amazon, drought, river levels, rainfall anomalies

1. Introduction

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River records suggest that on average, the Amazon experiences an extreme event - either a flood or a drought - every 10 years. In recent years, in the short span of five years, the Amazon Basin has been affected by severe droughts in 2005 and 2010 and a flood in 2009. Droughts in 1964, 1980 and 2005 were not linked to ENSO [See reviews in *Espinoza et al.,* 2009*; Yoon and Zeng*., 2010 and references quoted therein]. Overlying these short-term but severe events is evidence of decadal variations across the basin, although the northern part of the basin is out of phase with the southern part [*Marengo* 2009].

The 2010 drought started during an El Niño event in early austral summer of 2010 and then became more intense during La Niña in the austral winter dry season and the following spring. The impact of this dry season drought was particularly noticeable in the unusually low streamflow/levels in Amazon main stem and in several of its major tributaries, and in the higher surface temperatures and drier atmosphere which favored increased evaporation. In a recent paper, Lewis et al. (2011) determined that about 3.0 million km^2 were affected by drought in 2010, as compared to 1.9 million km^2 in 2005.

In the present study we use various rainfall and river data sets to verify the coherence of rainfall anomalies patterns and the extreme low river levels during the drought of 2010. We also investigate the occurrence of intense droughts, considering the long term variability of sea surface temperature (SST) anomalies in the tropical Atlantic Ocean, and their influence on the extent of the dry season and on rainfall trends in Amazonia during the wet and dry season.

2. Data and methodology

The Global Precipitation Climatology Centre-GPCC (orias.dwd.de/GPCC/) gauge-based gridded precipitation data set is available for the global land surface only [*Rudolf et al.*, 2005]. These data are available as mean monthly precipitation totals, anomalies and percentages

from the long-term mean for 1951-2010. Time series for rainfall were built for the wet and dry seasons for Northern Amazonia (75ºW-50ºW, 5ºN-7.5ºS) and Southern Amazonia (75ºW-50ºW, 15ºS-5ºS). The wet/dry seasons in southern Amazonia were defined as December-March DJFM and July-October JASO, and for northern Amazonia they were defined as February-May FMAM and July-October JASO, according to the rainfall seasonal cycle [*Figueroa and Nobre* 1990]. The observed SST was provided by the UK Met Office Hadley Centre's HadISST data, which is available from January 1903 to the present (Rayner et al., 2003). The anomalies were calculated from the maximum length of each dataset. Analyses to assess rainfall extremes were performed using the quintiles method by *Xavier et al.,* [2002, see Supplemental material] across the Amazon.

Main-stem river discharge and level data sets from gauging sites in Brazilian Amazonia were provided by the Brazilian Water Agency (Agência Nacional de Águas – ANA). To characterize the long term level/discharge variability of the Amazon basin hydrology, station records of the Rio Negro at Manaus and the Amazon River at Óbidos were used from the beginning of their records (1903-2010 for Manaus, and 1928-1947, 1970-2010 at Óbidos). Supplemental information includes data from the Madeira River Basin (1968-2010 at Fazenda Vista Alegre station and 1970-1990 at Manicoré Station). Further details about the hydrological stations can be found in *Tomasella et al*., [2010].

3. Decadal and long term rainfall variability and large scale circulation during dry and wet seasons in Amazonia

Figure 1 shows time series of SST anomalies in the tropical South and North Atlantic, together with rainfall records over the dry season in northern and southern Amazonia, and annual minimum levels of the Rio Negro at Manaus and Amazon at Óbidos. In general, a

weak negative tendency during dry season precipitation is apparent in both southern and northern Amazonia starting in the mid 1970s; while from 1951 to the mid 1970s there is a slight increase, exhibiting the decadal rainfall variability in the region previously detected by *Marengo*, [2009], *Espinoza et al.,* [2009], *Li et al*., [2006].. However, the negative trends seem to be related to interannual rainfall variability rather than to a gradual rainfall decline.

Changes in large scale circulation associated with SST patterns are responsible for rainfall anomalies, particularly during austral summer and autumn (see Supplementary material). The hydrological impacts of these anomalies are experienced in the form of lower-than-normal river discharge not only in the wet period, but also during the following winter and spring dry seasons. Since the late 1970s, the SST anomalies in the tropical North Atlantic have gradually increased, reaching high values during 1980, 1998, 2005 and then in 2010, all of which coincide with drought years in the Amazon. During March to May (MAM) of 2010, the seasonal temperature anomaly was the largest (1.5 ºC) since 1923, exceeding the previous MAM record of about 0.9 ºC in 2005. In the dry season (JJA) the temperature anomalies reached 1 ºC and 0.9 ºC in 2010 and 2005, respectively, again two records since 1902. The warming the tropical North Atlantic exhibits an inter-decadal SST trend, of which at least 0.5 ºC can be attributed to global warming [*Trenberth and Shea*, 2006].

It is noted that the negative rainfall trends in the dry season precipitation in both northern and southern Amazonia are consistent with surface warming in the tropical North Atlantic, as well as a weakening in the moisture transport from the tropical north Atlantic. Something unique to the 2010 drought was the fact that it started during an El Niño episode during the first half of the year, which turned to La Niña in the second half. The tropical Atlantic was at least 1.5-2 ºC above average all year long, which is much higher than in other drought years. Such changes in rainfall, even during the dry season, have impacts on the hydrology of the region.

Thus, minimum water levels in Manaus and Óbidos also show a negative trend, consistent with the reduction of dry season precipitation in both sections of the basin. To rule out the possibility of decreasing water levels at Manaus and Óbidos being due to river bed erosion, the discharge series of the Amazon River at Óbidos and of the Madeira River (the most important southern tributary) at Fazenda Vista Alegre were also analyzed. (See Supplemental information).

4. Changes in the dry season?

The role that the dry season rainfall plays in the hydrology of the region becomes an important issue in terms of climate feedbacks, since it may affect the onset of the following rainy season. Besides this, levels and discharge of many rivers in Amazonia were at their lowest values, which combined with drier air conditions caused strong impacts on the population, such as mobility because the dry-out of floodplain lakes, increasing fish mortality due to hypoxia. Drier air conditions plus higher surface air temperatures during austral spring and winter favored a larger number of forest fires in September 2010 (about 200% higher as compared to September 2009-www.cptec.inpe.br).

Cox et al., [2008] found that dry season precipitation (July-October JASO) was correlated with the variability in the tropical Atlantic meridional SST gradient. Therefore, to understand the Amazonian droughts during the dry season, our analysis focused on the effects of the Atlantic SST anomalies on the JASO season. The droughts of 2005 and 2010 were both examples of dry-season rainfall strongly influenced by the tropical Atlantic north-south SST gradient all year long, although the wet season of 2010 was affected by El Niño. It is well known that warm SST anomalies in the equatorial Pacific during El Nino years are

particularly important for the wet-season rainfall, since they suppress convection in northern and eastern Amazonia *[Marengo et al 2008]*.

Following *Xavier* et al. [2002], a decadal analysis using 5 levels of percentiles from very wet to very dry was performed for the southern Amazonia region during the wet and dry seasons (See Table 1 in Supplementary Material). For the whole period (60 years), the frequency of dry or very dry events increases in southern Amazonia during the dry season. This result was also verified for northern Amazonia (not shown), although not as clearly. Furthermore, no noticeable long-term change is found in dry or very dry events during the wet seasons in both sections of the Amazon, even though there is a pronounced decadal variability, with more droughts in decades where more frequent El Nino events occurred.

In order to identify possible changes in the dry season length, we use the GPCC monthly data from 1951 to 2010, as well as the number of consecutive dry months, delimited by a maximum monthly rainfall of 100 mm, a threshold generally used as a criterion to identify dry months in Amazonia [*Sombroek,* 2001]. Previous studies of Amazonian rainfall have described rainfall variability, but very few provide an integration of all dry months in terms of the length, strength and regularity of the whole dry season, for both observed and projected rainfall [*Mahli et al.,* 2008, *Li et al.,* 2008]. Figure 2 shows a Hovmoller diagram with the distribution of monthly rainfall in southern Amazonia from GPCC data for 1951-2010. The isohyets of 100 mm/month, considered the indicator of the dry season, are shown by the bold black line. The figure shows that during the 1950s and 1960s, the dry season was longer, suggesting a late demise of the dry season and possibly a late onset of the rainy season. In the middle 1970s, during the climate shift, the dry season was shorter. Since the 1990s, there has been a tendency for a late demise of the dry season. Moreover, during the last 5 years, the dry

seasons have become longer, with early onset and late demises, exemplified by the conditions in 2010.

Changes in precipitation, particularly during the dry season, are probably among the most critical determinants of the climatic fate of the Amazon. Indeed, the slight increase of dry and very dry events in the whole Amazon region, and in the length of the dry season, particularly in southern Amazonia (Figure 2), are consistent with observed changes in southern Amazonia from 1970-99 by *Li et al* [2008], and with downward trends in the river data at Manaus and Óbidos (Figure 1).

These changes are consistent with projections of potential future decline in dry-season rainfall. From an ensemble of 23 global climate model (GCM) projections, indications are for significant Amazonian drying over the 21st century, with an intensification of the dry season [*Mahli et al.,* 2008]. Future projections show that warming in the tropical North Atlantic forces the ITCZ to migrate northwards and strengthen the Hadley Cell circulation on longer time scales, enhancing the duration and intensity of the dry season in much of southern and eastern Amazonia by 2100.

5. Hydrological analysis of the drought of 2010 and other drought events

In order to determine if the trend detected in the minimum annual water levels at Manaus after the 1970s appears in other statistics of the series, an analysis of trends in water levels associated with different levels of probability was carried out. For each year of the Manaus series, the water level duration curve from daily river data was determined. The water level duration curve is a cumulative frequency curve that provides the probability, expressed here as a percentage, of specified water-levels being equaled or exceeded. Figure 3 shows the time series at Manaus of the annual minimum level and the value for which there is a 75%

probability of exceedance (referred to as P75), extracted from the annual water level duration curve. Visual and numerical analysis indicates that the trend observed for the minimum water levels cannot be detected for values at P75 or lower exceedance probability levels. In other words, the trend observed in Figure 1 in Manaus and Óbidos series can be detected only for very low water levels (and consequently discharge), at the tail of the statistical distribution: the negative trend observed for the minimum water levels becomes evident for values for which there is a 80% probability of exceedance, and increases gradually for higher exceedance probabilities (data not shown). In an annual average, these values have low weight, which explains why statistical trend analysis detects no changes in the annual mean water level series. Considering that most of the annual discharge is a consequence of the wet season rainfall, which does not show significant trends, changes in the dry season shown in Figure 2 affect river discharge only marginally. The annual water balance demonstrates that with the gradual increase of rainfall at the end of the dry season, there is a slight recovery of discharge and basin storage in October. Therefore, the demise of the dry season identified in Figure 2 seems to be influencing the recovery of river discharge late in the dry season, when river water levels are very low.

6. Discussions and conclusions

An analysis of the climate situation indicates that the drought of 2010 was unique, since it differed both from previous El Niño-related and non El Niño severe droughts. Changes in circulation regimes leading to the drought were associated with the warming of the tropical North Atlantic, which was even warmer than in the previous drought of 2005. The warming in the tropical North Atlantic during 2010 was the strongest of the whole 1903-2010 period, and was at its highest during March-May, which is the season when the mean climatological

position of the ITCZ is over central and eastern Amazonia, and this forced the ITCZ to be located anomalously northward displaced of its climatic position, by about 5°.

Changes in precipitation have been detected particularly in the dry season in both northern and southern Amazonia, while no noticeable change has been observed in the wet season precipitation. The slight increase of dry and very dry events in the whole Amazon region, and particularly in southern Amazonia during the dry season is concomitant with an increase in the length of the dry season. These changes have impacted the recession of major rivers of the Amazon Basin, explaining downward trends of low water levels. The identified changes fit in the category of decadal variability, and should be taken in the context of the observed trends towards higher SSTs in the tropical North Atlantic discussed above, and with the results from *Trenberth and Shea* [2006], who attribute a portion of the warming in the North Atlantic to global warming.

Our results suggest that changes in the dry season and hydrology of the Amazon Basin are related to SST warming in the tropical North Atlantic. The changes observed in the length and intensity of the dry season have influence over the very low river water levels and discharge at the end of the dry season. Given the increasing human occupation and severe land use changes that Amazonia has been undergoing in the last two decades, decadal variations in the intensity and extension of the dry season, associated with changes in the dry season drought frequency and intensity, will have profound environmental and social impacts in the region.

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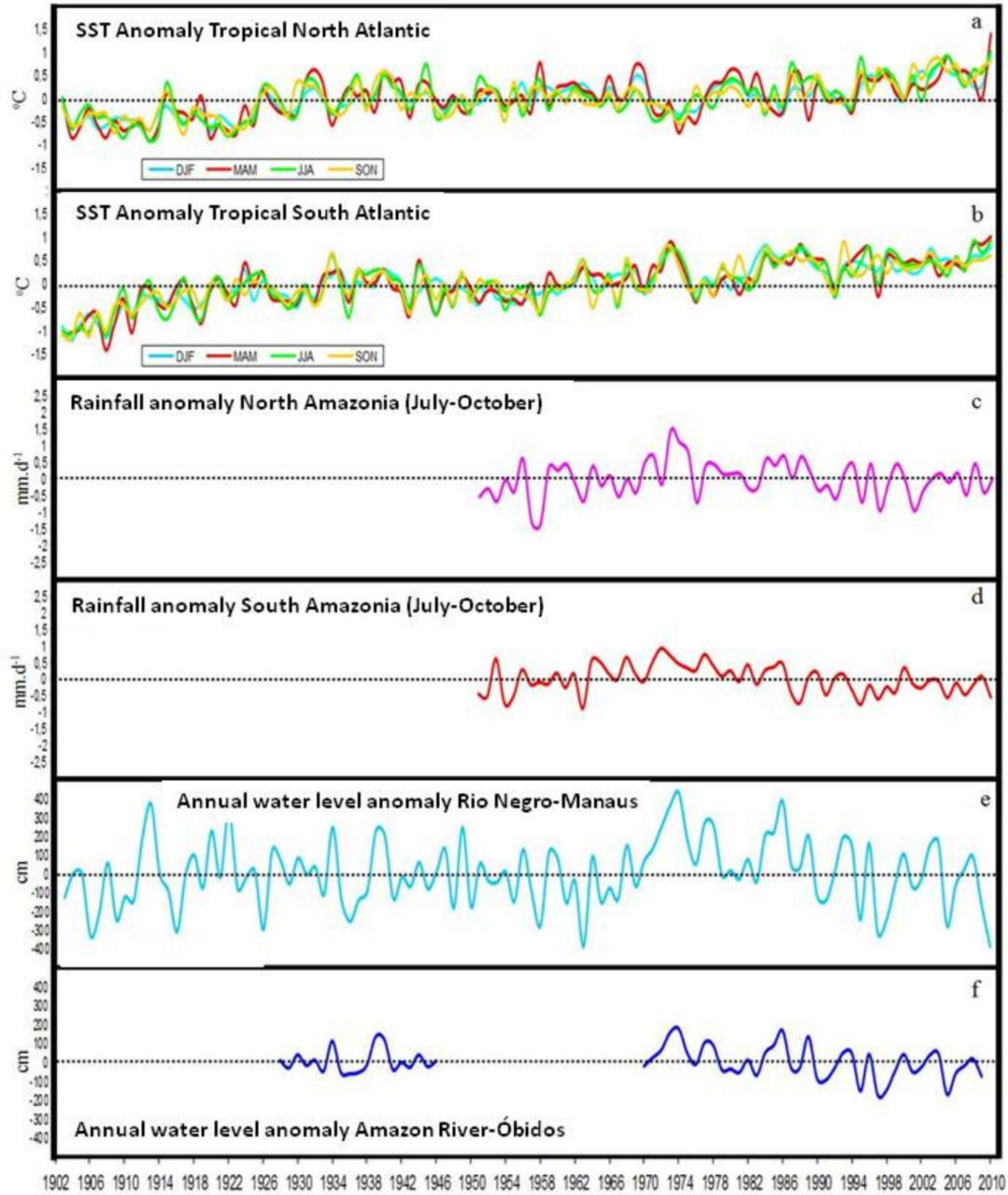
Figure captions:

FIG 1. Seasonal time series of SST anomalies in tropical North Atlantic (a) and South Atlantic (b), for 1903 to 2010.; GPCC rainfall for the dry season July-October JASO in northern and southern Amazonia (c, d) for 1951-2010; annual minimum levels of the Rio Negro in Manaus (e) for 1903-2010; and discharges of the Amazonas in Óbidos (f) for 1928‑1947, 1970-2010. Units are in °C in (a) and (b), $mm.d^{-1}$ in (c) and (d) and cm in (e) and (f). Base period for calculations of the anomalies are from the mean of all data sets

FIG 2. Hovmoller diagram of monthly rainfall from 1951 to 2010 for southern Amazonia. Units are in mm/month. The 100 mm/month isohyet is marked in bold and is an indicator of dry months, after (Sombroek 2001).

FIG 3. Time variation of minimum water level (Minimum) and values at the 75% exceedance probability level (P75) of the Negro River at Manaus Harbor (a); Time variation of the difference between values at the 75% exceedance probability level and minimum water levels (P75 – Min) (b).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SST Anomaly Tropical South Atlantic
b
Rainfall anomaly North Amazonia (July-October)
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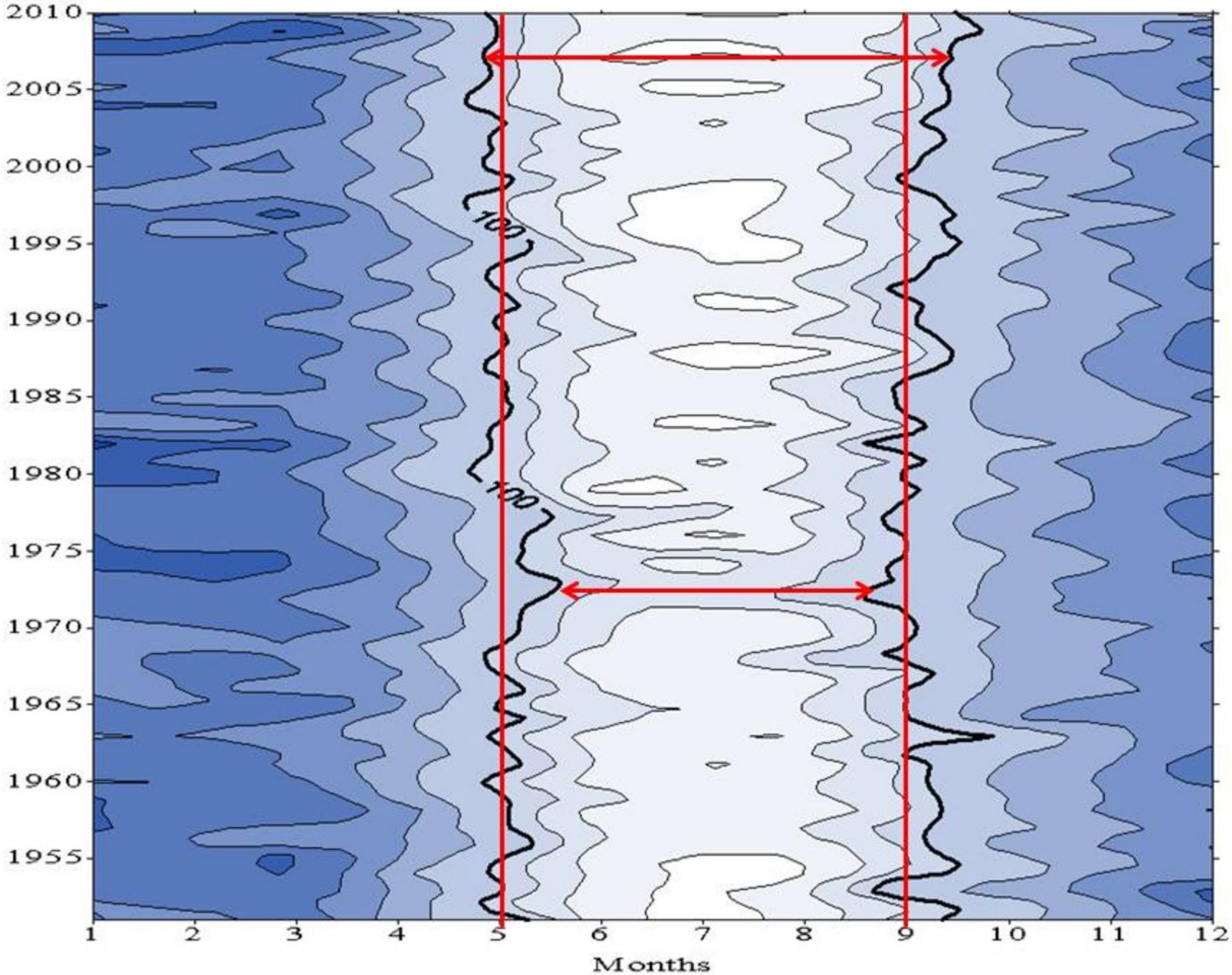
mm.d-1
Rainfall anomaly South Amazonia (July-October)
d
Annual water level anomaly Rio Negro-Manaus
e
cm
f
Annual water level anomaly Amazon River-Óbidos
1902 1906 1910 1914 1918 1922 1926 1930 1934 1938 1942 1946 1950 1954 1958 1962 1966 1970 1974 1978 1982 1986 1990 1994 1998 2002 2006 2010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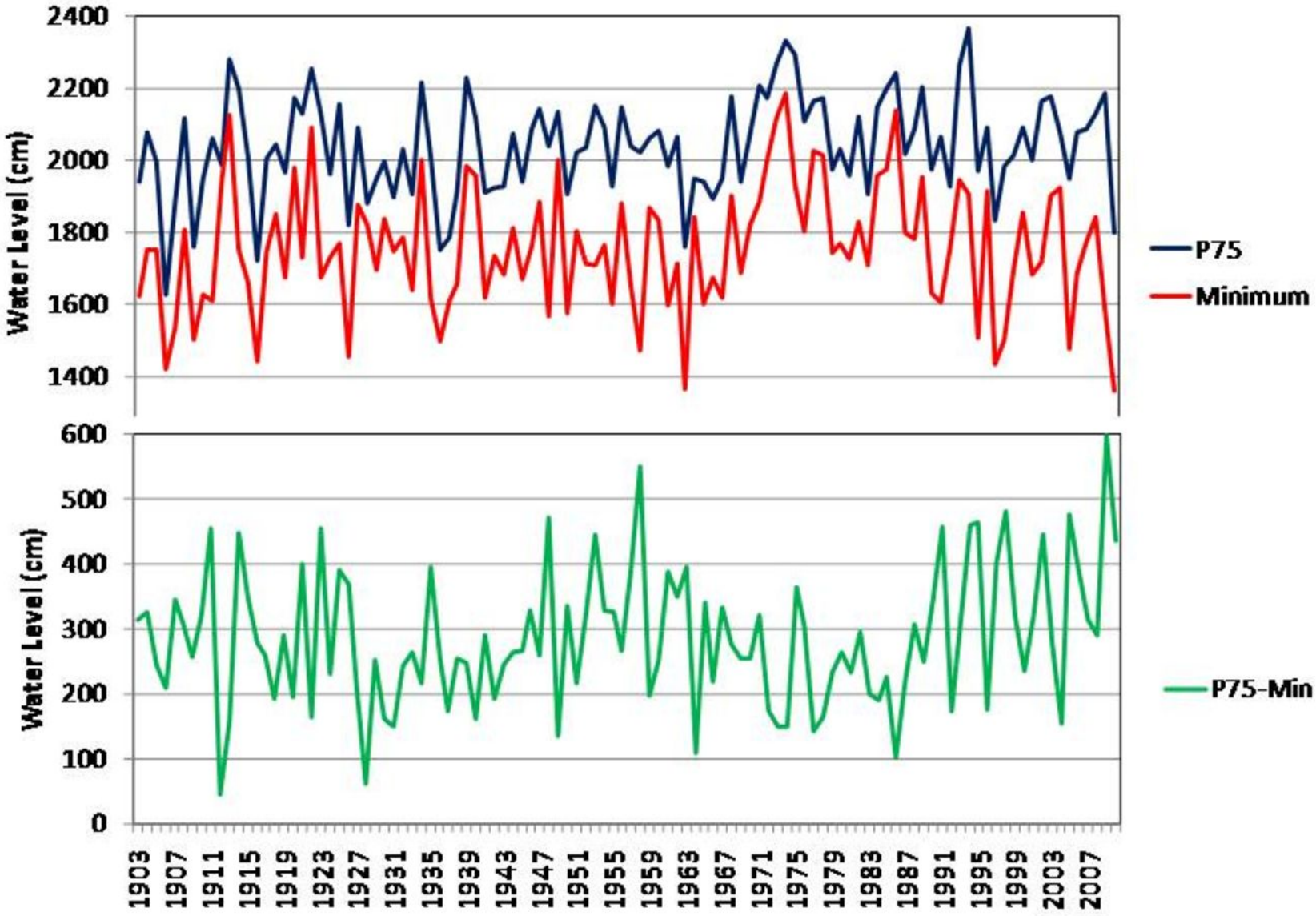
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