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The droughts of 1996–1997 and 2004–2005 in Amazonia: hydrological response in the river main-stem

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Abstract:

Severe hydrological droughts in the Amazon have generally been associated with strong El Niño events. More than 100 years of stage record at Manaus harbour confirms that minimum water levels generally coincide with intense warming in the tropical Pacific sea waters. During 2005, however, the Amazon experienced a severe drought which was not associated with an El Niño event. Unless what usually occurs during strong El Niño events, when negative rainfall anomalies usually affect central and eastern Amazon drainage basin; rainfall deficiencies in the drought of 2005 were spatially constrained to the west and southwest of the basin. In spite of this, discharge stations at the main-stem recorded minimum water levels as low as those observed during the basin-wide 1996–1997 El Niño-related drought. The analysis of river discharges along the main-stem and major tributaries during the drought of 2004–2005 revealed that the recession on major tributaries began almost simultaneously. This was not the case in the 1996–1997 drought, when above-normal contribution of some tributaries for a short period during high water was crucial to partially counterbalance high discharge deficits of the other tributaries. Since time-lagged contributions of major tributaries are fundamental to damp the extremes in the main-stem, an almost coincident recession in almost all tributaries caused a rapid decrease in water discharges during the 2005 event. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS drought; Amazonia; hydrological response

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INTRODUCTION

The Amazon Basin—with a drainage area of about 6·1 Mkm^2, a mean discharge of about 200 900 $m^3 s^{-1}$, (Molinier, 1992) equivalent to 15% of global freshwater that flows into the oceans and home of the world largest tropical rainforest—has captured the attention of the scientific community for decades. Because of the sheer size of the Amazon Forest, which includes a variety of climate and hydrological regimes, soil types, landscapes and stunning biodiversity, and where physical, chemical and biological interactions occur at different time and spatial scales, a complete understanding of how the Amazon functions as a regional entity for the Earth system remains one of the most fascinating scientific challenges.

The Amazon Basin is less disturbed by anthropogenic actions in comparison to the world's large river basins (Richey *et al*., 2004). It provides a unique opportunity to improve our understanding on how pristine environments function, in particularly during extreme climatic events. In recent years, the Amazon Basin has experienced a series of extreme climate events with strong ecological and social impact on local population, namely a drought in 2005 and large floods in 2006 and the largest flood on record in 2009.

Moreover, recent studies based on numerical models suggest that the Amazon is highly vulnerable to a suite of anthropogenic drivers of environmental change: global climate change (Cox *et al*., 2004, 2008; Li *et al*., 2006; Salazar *et al*., 2007), deforestation (Costa *et al*., 2007; Sampaio *et al*., 2007) and increased forest fires (Cardoso *et al*., 2003; 2009; Brown *et al*., 2006) and has the potential to accelerate those changes by feedback mechanisms towards tipping points when changes become irreversible (Cox *et al*., 2008; Nobre and Borma, 2009). Bearing in mind that future scenarios suggest an increase in frequency and intensity of extreme climatic events, a better understanding of how Amazon ecosystems cope with environmental extremes is crucial not only to assess the degree of vulnerability of the whole natural system to human perturbations but also to improve the ability to model such extremes and consequently reduce the uncertainties of future climate scenarios applied at a regional scale.

The goal of this study is to analyse the drought of 2005 from a hydrological perspective and understand why this event caused severe social and ecological impacts. Indeed, the drought of 2005 showed unique characteristic, when compared to the droughts that normally affect the basin, and consequently has became a 'study case' to understand Amazon forest response to a climate extreme. The 2005 drought has been studied from a meteorological (Marengo *et al*., 2008a,b; Zeng *et al*., 2008), ecological (Aragão *et al*., 2007; Saleska *et al*., 2007; Phillips *et al*.,

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2009; da Costa *et al.*, 2010; Samanta *et al.*, 2010), remote sensing (Asner and Alencar, 2010) and human perspective (Brown *et al.*, 2006; Aragão *et al.*, 2008; Boyd, 2008). However, the hydrological aspects of that drought event have not been addressed in their full extent so far.

Previous to the event of 2005, the Amazon experienced a more typical El Niño-induced meteorological drought during 1997–1998. El Niño-type events generally cause pronounced rainfall deficits over central, northern and eastern Amazonia (Marengo, 2009). The drought of 2005, on the other hand, was related to warm sea surface anomalies in the tropical North Atlantic ocean, leading to negative rainfall anomalies mostly over western and southeastern portions of the Basin. In spite of these differences, the impact of both droughts on the main river floodplain has been considered relatively similar. To that end, this paper will discuss and compare the hydrological response of the Amazon Basin of both episodes, highlighting its similarities and differences. A forthcoming paper will analyse the ecological and human impact of both droughts on the river floodplain.

A BRIEF DESCRIPTION OF THE HYDROLOGICAL CHARACTERISTICS OF THE AMAZON BASIN

This section provides a general characterization of the Amazon Basin macro-scale hydrology. Further details about the hydrological characteristic of the Amazon can be found in Molinier *et al.* (1996), Meade *et al.* (1991), Richey *et al.* (2004), Marengo (2009) and among others.

The Amazon drainage basin includes areas of extremely high altitude (Andes and sub-Andean trough) which drains to large areas of very low reliefs (shield areas and alluvial plain). Because of the geological history and the high amounts of rainfall in the Amazon region, the upper basin is dominated by andosols, while the low topographic gradients in the middle and lower basin led to the development of highly weathered oxisols and ultisols (Richey *et al.*, 2004).

Due to the differences in rainfall regime between the northern (continental rainfall influenced by the meridional displacement of the Intertropical Convergence Zone—ITCZ) and southern tributaries (resulting from organized convection in southern Amazonia modulated by the South Atlantic Convergence Zone—SACZ during the austral summer), the maximum rainfall in the southern part of the basin occur 2 months earlier (December–January–February) than maximum rainfall over the central basin main-stem (February–March–April) and 6 months earlier than over the northern part of the basin (June–July–August). Minimum rainfall at the south of the basin occurs in June–July–August, 6 months earlier than the minimum on the northernmost portion, which are in January–February–March (Figueroa and Nobre, 1990; Meade *et al.*, 1991; Marengo, 1992, Molinier *et al.*, 1996).

For this reason, the Amazon Basin is generally divided into three main hydrological sub-regions: (i) the southern tributaries, (ii) the northern tributaries and (iii) the main river floodplain, which receives the water from the tributaries from both hemispheres (Figure 1). Drainage areas of tributaries range from thousand to millions square kilometres.

Among the southern tributaries, the Juruá and Purús rivers drain the sub-Andean trough and the central plain.

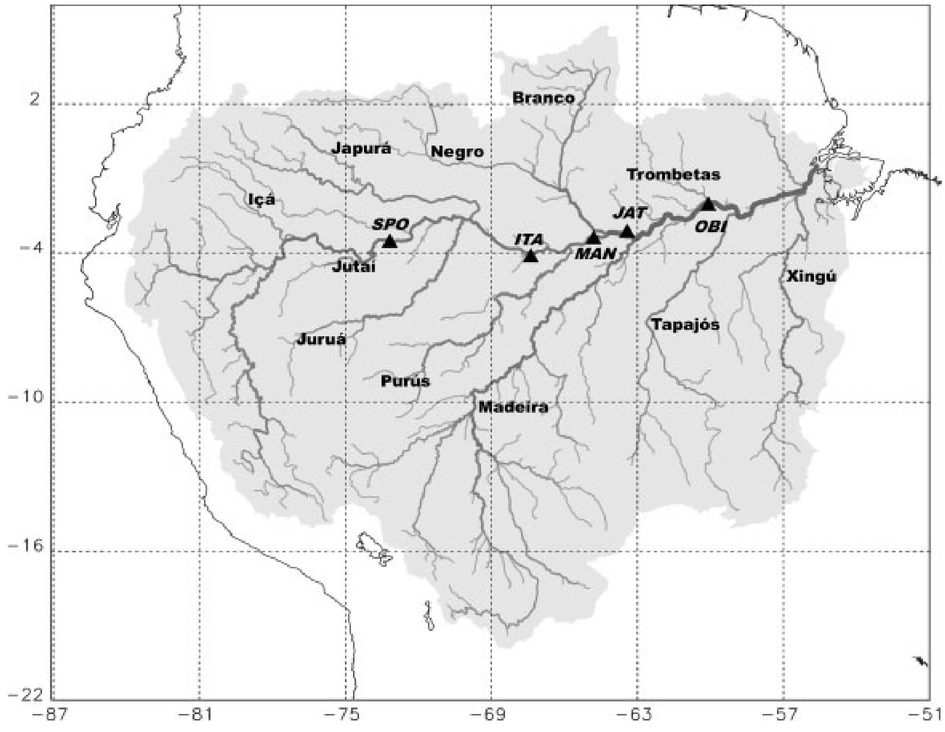

Figure 1. The Amazon River and its main tributaries. Black triangles indicate the locations of main-stem discharge stations: São Paulo de Olivença—SPO; Itapeuá—ITA; Manacapurú—MAN; Jatuarana—JAT and Óbidos—OBI

Peak flows in the Purús River precede the peak of the Solimões by a month or two (Meade *et al.*, 1991).

The Madeira River is the most important of all the southern tributaries. The Madeira, born in the Bolivian Andes, crosses the Brazilian Highlands and finally flows into the central plain. The peak flow of the Madeira River occurs normally 2 months earlier than the peak of the Amazon River at the confluence of both rivers (Meade *et al.*, 1991).

On the southeastern part of the basin, the Amazon receives two large tributaries: the Xingu and Tapajós rivers, both with headwaters in the *cerrado* (savanna) and transitional forest draining from the Brazilian Highlands to the central floodplain.

Regarding the northern tributaries, the Içá and Japurá rivers originate in the Colombian Andes, flow across the sub-Andean trough and finally reach the central plain. The Negro River is a non-Andean river who has its headwaters on the Guianas Shield, draining areas of savanna of northern Brazil and Venezuela, then flows southeastward on the central plain where it receives the contribution of other rivers such as the Branco River, to finally reach the main-stem by the city of Manaus. On average, the highest stages in the Negro River occur 2 to 3 months later than in the Madeira River, while the minimum water level in the Madeira River occurs 4 to 5 months later than the lowest stage in the Negro River (Meade *et al.*, 1991). Finally, and to the east, the Trombetas River, with headwaters also in the Guianas Shield, drains southward towards the central floodplain.

Within the Brazilian territory, the contribution of northern and southern tributaries is almost the same: 46 and 54%, respectively (Molinier *et al.*, 1996). The contributions of the northern and the southern basins are equivalent because the smaller northern basins are rainier than the large southern basins (Espinoza Villar *et al.*, 2009). The Amazon River, born in Peruvian Andes, changes its name along its path: Marañón River from headwaters through the border Peru-Brazil; Solimões River as it enters Brazil and finally Amazon River downstream the confluence of the Solimões with the Negro River. The Amazon main-stem is an extensive floodplain with an intricate network of drainage channels and permanent lakes of variable size, which communicate with the main river during the periodical inundations and remain isolated during the low water (Richey *et al.*, 2004). Small tributaries drain riparian areas to the main-stem, while large river branches act as diversion canals between the main channel and the tributaries and communicate the lake system to the main channel depending on water stage.

As described by Richey *et al.* (2004), the main river course can be characterized by several sections. Each section has distinctive river morphology determined by topographic and structural features. Therefore, the relationship of the main-stem with the diversion canals and the system of floodplain lakes varies along the main course. A detailed description of the geomorphological aspects of the floodplain system is presented by Latrubesse and Franzinelli (2002).

The floodplain characteristics determine the influence of in-channel storage and floodplain storage on the main-stem hydrograph (Richey *et al.*, 1989; Vörosmarty *et al.*, 1989) and play a fundamental role in damping flood waves in the main river. Consequently, and for the purpose of this paper, the river course upstream of São Paulo de Olivença was treated as upper Amazon, dominated by the Andes discharge, while downstream of Óbidos the river was classified as lower Amazon, where the influence of the Guyana and Brazilian shield waters are maximized. Between both sections, 'mixed waters' define the middle Amazon (Figure 1). Table I summarizes hydrological characteristics of the Amazon main-stem and of the most important tributaries.

Floodplain lakes are crucial for the reproduction and survival of a large number of fish species (Junk *et al.*, 2007), and extreme droughts such as those of 1996–97 and 2004–2005 have been associated by local population with greater fish mortality rates in the floodplain lakes by hypoxia. Spatial and temporal inundation of the main-stem floodplain controls the production dynamics

Table I. Hydrological characteristics of the Amazon River main-stem and major tributaries

River	Drainage area (km^2)	Rainfall (mm year^{-1})	Annual mean discharge (m^3 s^{-1})
Main-stem			
Solimões (São Paulo de Olivença)	990 780	2900	46 500
Solimões (Itapeuá)	1 769 000	n/a	85 485
Solimões (Manacapurú)	2 147 740	2880	103 000
Amazonas (Jatuarana)	2 854 300	2780	131 600
Amazonas (Óbidos)	4 618 750	2520	168 700
Northern tributaries			
Içа	143 760	3160	8800
Japurá	248 000	3000	18 620
Negro	696 810	2566	28 400
Trombetas	128 000	1822	2 555
Southern tributaries			
Jutaí	77 280	2781	3 020
Juruá	185 000	2452	8 440
Purus	370 000	2336	11 000
Madeira	1 420 000	1940	31 200
Tapajós	490 000	2250	13 500
Xingu	504 300	1930	9 700
Whole basin			
Amazon	6 112 000	2460	209 000

n/a, not available. Both rainfall and discharges correspond to the period 1973–1990. In the case of the main-stem, mean annual discharges and drainage area were calculated at the gauging station indicated in parenthesis. As for the tributaries, the drainage area was estimated at the confluence of the tributary with the Amazon main-stem, while the mean annual discharge was extrapolated at the confluence by flow regionalization. The last row indicates an extrapolation of discharge for the whole basin (source: Filizola, 1999; Molinier, 1992; Molinier *et al.*, 1996).

of planktonic and periphytic algae, and the phenological development of free fruits and seed (Melack *et al.*, 2009). Therefore, the distribution of feeding habitats of herbivorous and omnivorous fish is closely link to the annual flooding pulse. Besides this, local population mobility is entirely dependent on the communication between large river branches and floodplain lakes, which are heavily constrained during the severe droughts, causing impacts on local economy, education and medicine supply. Therefore, it is clear that the impacts of severe drought on the main-stem floodplain should not be underestimated.

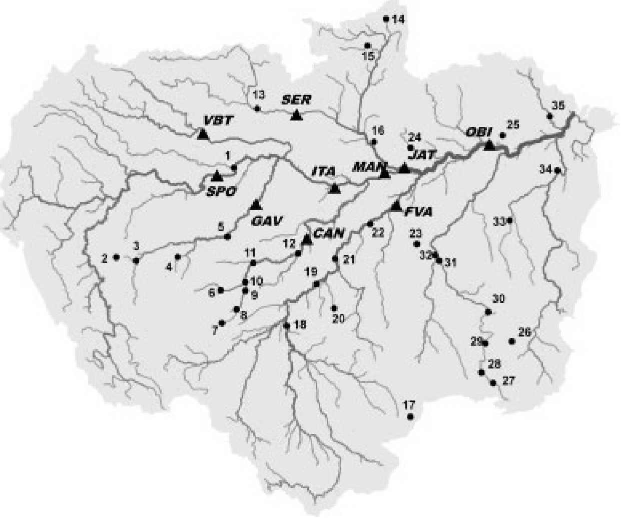

Figure 2. Discharge stations, with data available since 1978 or earlier, used to characterize the drought. Black triangles show the location of representative discharge stations, while black circles indicate the location of secondary discharge stations. Labels are listed as code in Table II

DATA

All the hydrological data used in this paper were extracted from the Brazilian Water Agency—Agência Nacional de Águas (ANA) database. The data were quality-controlled following the methodology described in ANEEL (1982). Only those ANA gauging stations with data available since 1978 or earlier were selected. Monthly discharge data were organized and analysed according to the hydrological year November–October. Therefore, the 1996–1997 drought refers to the period November 1996–October 1997, while the 2004–2005 drought corresponds to November 2004–October 2005. For the period 1978–2006, statistics such as the mean and standard deviation were calculated for all the selected discharge stations.

The reason for selecting the period 1978–2006 is related to the fact that a large number of ANA discharge stations began to operate in 1977, allowing a better spatial representation extreme events after that date. Discharge stations were divided into two groups. The first group includes those stations located on the main-stem and on each of the major tributaries. Whenever more than one discharge station was available in a particular tributary, we selected the stations located as close as possible to the confluence with the main-stem. Remaining stations were classified in the second group.

The first group corresponds to the most representative stations from a basin-wide perspective, since it comprises most of the contributions coming from major tributaries and, in addition, indicates how this signal is transmitted along the main-stem. It should be noted, however, that not all the tributaries have discharge stations with contributing area sufficiently representative of the whole drainage area and with flow data available for the time period used in this study. The second group was treated as ancillary information and was used to characterize the drought spatially.

Table II indicates the coordinates, the discharge area and the mean annual discharge for the period 1978–2006. For the representative discharge stations, Table II also indicates the fraction of the catchment that the station drains divided by the sub-basin total area and the distance of the station to the confluence with the main-stem. The location of representative and secondary discharge stations is shown in Figure 2, where the data labels are listed as code in Table II.

The ANA database provides stage records, field flow measurements and historical series of river discharge derived from the station ratio curve. In the case of Fazenda Vista Alegre (Madeira River), discharge data were not available in the ANA database because river stages are affected by backwater effects (Meade *et al.*, 1991). Since the most representative data from the Madeira River is essential for the analyses of this paper, two ratio curves were built, one for rising stages and the other for falling stages. Both the curves were stable for all the period analysed.

RESULTS AND DISCUSSION

The geographical context of the hydrological drought of 2005

Figure 3 indicates the geographical location of discharge stations with monthly discharge below 1 SD (in relation to the mean) between November 2004 and October 2005, depicting the location of river stations which experienced below-the-mean discharges. As mentioned above, mean and standard deviation were calculated based on 1978–2006 mean discharges.

Between November 2004 and January 2005, few discharge stations in the southwest of the basin showed lower-than-normal discharges, which are likely to be related to rainfall deficits in isolated areas. During February and March 2005, significant lower-than-the-mean discharges appeared in the Madeira Basin, and, by May 2005, the signals were extended to the Purus Basin.

During May and June 2005, lower-than-the-mean discharges persisted in the Madeira and Purus basins, and this signal began to appear in the upper Solimões, Juruá, Japurá and Negro rivers. In July 2005, lower-than-normal discharges were concentrated in the main-stem, clearly

Table II. Representative and secondary ANA discharge stations used to characterize the drought

Code	Station	River	Lat	Long	Station drainage area (1000 km^2)	Mean annual discharge 1978–2006 (m^3 s^{-1})	Approximate distance to the mouth (km)	Percentage of the sub-basin
				Representative discharge stations				
SPO	São Paulo de Olivença	Solimões	−3·45	−68·75	990 781	46 320·7	2535	16·2
GAV	Gavião	Juruá	−4·84	−66·35	162 000	4727·9	296	87·6
VBT	Vila Bittencourt	Caquetá/Japurá	−1·40	−69·43	197 136	13 736·0	588	79·5
ITA	Itapeuá	Solimões	−4·05	−63·03	1769 000	83 761·7	700	28·9
CAN	Canutama	Purus	−6·53	−64·38	230 012	6555·5	655	62·2
MAN	Manacapurú	Solimões	−3·31	−60·48	2147 736	101 036·0	1384	35·1
SER	Serrinha	Negro	0·48	−64·88	279 945	17 810·6	704	40·2
JAT	Jatuarana	Amazonas	−3·05	−59·12	2854 286	124 411·8	1210	46·7
FVA	Fazenda Vista Alegre	Madeira	−4·90	−60·03	1324 727	28 827·1	249	93·3
OBI	Óbidos Linígrafo	Amazonas	−1·95	−55·51	4680 000	169 943·1	700	76·6
				Secondary discharge stations				
1	Santo Antonio do Içá	Solimões	−3·08	−67·93	1134 540	55 044·9		
2	Serra do Moa	Moa	−7·44	−73·65	1099	31·2		
3	Cruzeiro do Sul	Juruá	−7·61	−72·68	38 537	889·3		
4	Envira	Tarauacá	−7·43	−70·66	48 317	1191·3		
5	Santos Dumont	Juruá	−6·44	−68·40	142 234	4044·2		
6	Seringal da Caridade	Purus	−9·04	−68·57	63 166	1367·0		
7	Xapuri	Acre	−10·65	−68·51	11 765	223·6		
8	Rio Branco	Acre	−9·98	−67·80	22 670	351·7		
9	Floriano Peixoto	Acre	−9·05	−67·37	33 469	641·6		
10	Valparaíso Montante	Purus	−8·68	−66·98	103 285	1998·5		
11	Seringal Fortaleza	Purus	−7·72	−66·02	158 166	3783·0		
12	Lábrea	Purus	−7·26	−64·80	220 351	5555·8		
13	Curicuriari	Negro	0·20	−66·00	194 462	12 473·1		
14	Maloca do Cantão	Cotingo	4·17	−60·03	5815	151·1		
15	Fé e Esperanca	Mucajaí	2·87	−61·23	13 658	288·8		
16	Caracarai	Branco	0·18	−61·27	124 980	2753·8		
17	Pontes e Lacerda	Guaporé	−15·22	−59·35	3140	60·4		
18	Guajará Mirim	Mamoré	−10·79	−65·35	589 497	8306·3		
19	Porto Velho	Madeira	−8·74	−63·92	954 285	19 175·1		
20	Ariquemes	Jamari	−9·93	−63·06	7295	177·9		
21	Humaitá	Madeira	−7·51	−63·02	1 066 240	23 120·4		
22	Manicore	Madeira	−5·82	−60·98	1 157 516	27 012·6		
23	Santarem Sucunduri	Sucunduri	−6·80	−59·04	12 631	435·4		
24	Cachoeira Morena	Uatumã	−2·11	−59·85	20 394	654·7		
25	Boca do inferno	Curuá	−1·50	−54·17	20 803	136·0		
26	Porto dos Gaúchos	Arinos	−11·54	−54·42	36 913	726·3		
27	Porto Roncador	Teles Pires	−13·57	−55·33	10 571	276·2		
28	Lucas do Rio Verde	Verde	−13·05	−55·12	5435	119·0		
29	Cachoeirão	Teles Pires	−11·65	−55·07	34 589	820·1		
30	Indeco	Teles Pires	−10·11	−55·73	52 190	1170·4		
31	Três Marias	Três Marias	−7·61	−57·87	138 586	3642·7		
32	Barra do São Manuel	Barra do São Miguel	−7·34	−58·37	332 163	8200·9		
33	Cajueiro	Curuá	−5·65	−54·22	34 693	829·1		
34	Altamira	Xingu	−3·21	−52·72	446 203	8015·7		
35	São Francisco	Jari	−0·57	−52·57	51 343	1006·5		

The geographic locations are indicated in Figure 2, where the labels correspond to the column 'Code'. For the representative stations, the percentage of the sub-basin is the fraction of the stations drainage area divided by the whole sub-basin drainage area; the distance to the mouth indicates, in the case of tributaries, how far the discharge station is to the confluence with the main-stem and, for the main-stem stations, distance to the Amazon mouth.

related to discharges deficits from the southwestern tributaries.

Between August and September 2005, lower-than-normal discharges were generalized along the main-stem and in the western and southwestern tributaries. By October 2005, below-the-mean discharges were not observed in the headwaters of the tributaries, but they were persisting in the lower basin of the western and southwestern tributaries and in the main-stem. Therefore, from a hydrological standpoint, the manifestation of the 2004–2005 drought on discharges was geographically constrained: it began in the Madeira River by the beginning of 2005; it intensified and was observed in adjacent tributaries during the second quarter of 2005 and heavily impacted the main-stem during September and October 2005. Since the hydrological data from Peru and

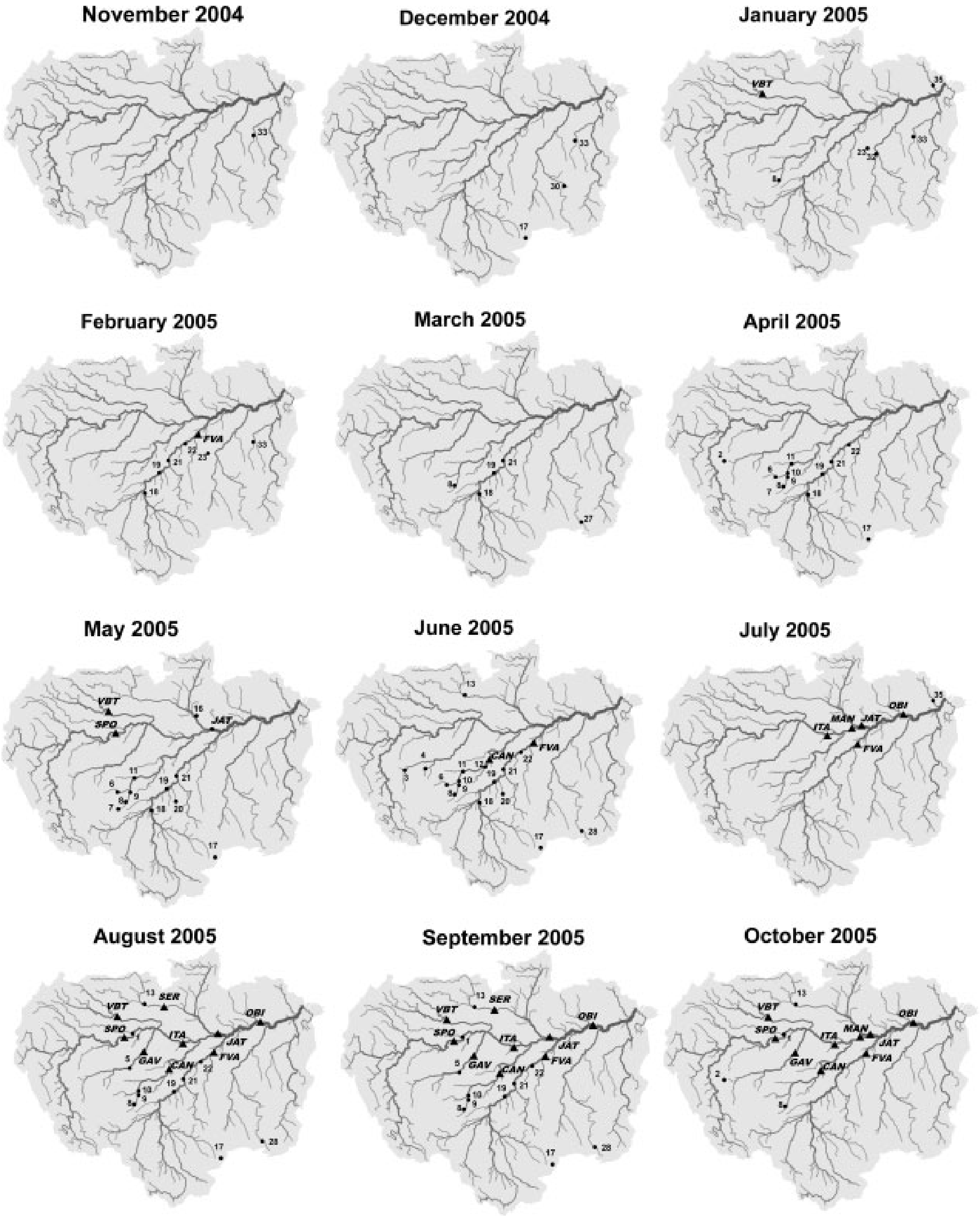

Figure 3. Geographical location of discharge stations with flow values below 1 SD between November 2004 and October 2005. Labels are listed as code in Table II

Bolivia were not available, it was not possible to describe the temporal dynamics of the 2004–2005 drought in those countries in detail. The data presented by Marengo *et al.* (2008a) and Zeng *et al.* (2008) showed that the levels of the Solimões River in Iquitos started to drop from January 2005.

Rainfall anomalies maps presented by Marengo *et al.* (2008a,b) indicated that most of the region experienced rainfall deficiency between late 2004 and early 2005. After April 2005, rainfall anomalies became strongly negative (larger than 100 mm month^{-1}) in the south and west of the basin, in agreement with the results presented in Figure 3, which shows a larger number of stations with significantly low discharge concentrated in the southwestern tributaries between April and June 2005. Downstream, water levels in the main-stem were above normal during March to May 2005 and then suddenly dropped from May to October 2005, clearly a response to lower-than-normal discharges recorded upstream.

In summary, this analysis suggests that the lower discharges recorded along the main-stem were originated in tributaries located in the western and southwestern part of the basin and were propagated to the main river during the low water period.

Hydrological behaviour of the 2005 drought compared to the 1997 El Niño-related drought

As mentioned before, rainfall in the Amazon Basin is related to the continental convective activity influenced by large-scale meteorological systems such as the ITCZ and the SACZ. These systems are planetary scale and particularly sensitive to sea surface temperatures (SSTs) of both the Tropical Atlantic and Pacific Oceans. Several studies (Marengo, 1992; Ronchail *et al.*, 2002) have identified negative rainfall anomalies in Amazonia to be associated with the presence of warmer-than-normal surface waters in the tropical Pacific, the well-known El Niño-Southern Oscillation (ENSO), and with warmer SST anomalies in the tropical North Atlantic.

During strong El Niño episodes, intense subsidence over the Amazon and an anomalously northward displaced ITCZ over the tropical Pacific and Atlantic Oceans tends to inhibit rainfall in central and western Amazonia (Marengo *et al.*, 2008a). The severe droughts that affected the Amazon in 1982–1983, and 1997–1998, for instance, have been associated with intense warming of sea water in equatorial Pacific and the tropical Atlantic also.

In contrast to the intense drought of 1997–1998, the drought of 2004–2005 was not associated with the occurrence of an El Niño episode. Based on the reanalysis data, Marengo *et al.* (2008a) concluded that southwestern Amazonia and the upper Solimões river region were affected by 'weaker convection or even subsidence' during the onset of the rainy season during late 2004 and the beginning of 2005, which inhibited rain formation. This process, according to Marengo *et al.* (2008a), has been induced by the presence of anomalously warm water in the tropical North Atlantic, while SSTs in the Pacific were near-normal. Warmer tropical North Atlantic SSTs gave rise to a perturbed Hadley-type circulation with anomalous rising branch over the tropical Atlantic and anomalous subsidence over parts of the Amazon. This anomalous pattern reflected a weakening of the moisture transport from the tropical North Atlantic into the Amazon region, and also the transport of moisture from the northern Amazon into the southern Amazonia during early austral summer of 2005. Another historical event, with the same characteristics of the 2004–2005 drought, has been recorded in 1963–1964 (Marengo *et al.*, 2008a). Therefore, the typology of such drought is much more infrequent in comparison to the more common El Niño-induced droughts.

Since the drought of 2004–2005, in terms of the physical mechanisms, geographical extension and duration, was quite different to the severe droughts associated with El Niño episodes, it is crucial to understand how rainfall anomalies, subsumed only to the western and southwestern of the Amazon Basin, severely impacted the hydrological regime of the river on a basin-wide scale.

The 1997–1998 El Niño episode started in March–April 1997, intensified from June to September 1997 reaching its mature phase and then faded away by May 1998 (Kane, 1999). Therefore, the 1997–1998 El Niño event was more intense during the austral spring of 1997, when most of the Amazon Basin (the drainage area located in the Southern Hemisphere) was in the transition from dry to wet season; the episode became weaker during the late austral wet season by March 1998 and had dissipated by June 1998, that is, the beginning of the dry season of the Southern Hemisphere. This is why, in hydrological terms (thus is, river discharges during the recession), the effects of the mega El Niño episode of 1997–98 were strongest in the hydrological year of November 1996–October 1997, rather than the hydrological year that began in November 1997. It is important to note that the effects of this El Niño episode were detected in river discharges throughout 1998, though with less intensity than the dry season of 1997. Therefore, in order to compare the hydrological impacts of two extremely significant droughts that affected the low water season in the main-stem, this study compares the hydrological years of 1996–1997 and 2004–2005.

Figures 4 and 5 show monthly river discharges with mean discharges (for the period 1978–2006) along the main-stem and for selected tributaries, during the 1996–1997 and 2004–2005 droughts, respectively. Figure 4 indicates that, along the main-stem, discharges were close to the long-term mean between November 1996 and February 1997. During the high water season of 1997, water discharges were consistently above the mean along the main stem and then an abrupt recession began.

In São Paulo de Olivença, at the upper Amazon Basin, discharges were below average until February 1997 and became above average during the high water season through June 1997. Then, the recession proceeded with discharges lower than the mean throughout the rest of the year. By October 1997, discharges reached the minimum values and the deficit in relation to the mean was maximum. Historical records from the port of Manaus (which is the oldest stage record available in the Amazon Basin) indicate that the levels at the port of Manaus were lower than normal throughout most of the year during strong El Niño episodes: the 1982–1983 and 1997–1998, and even lower during El Niño 1925–1926 droughts (Meggers 1994; Marengo *et al.*, 2008a; Williams *et al.*, 2005). It is important to note that water stages at the port of Manaus, located in the Negro River, reflect also the signal of the Solimões River because of strong backwater effects (Filizola *et al.*, 2009).

In the middle Amazon River, the discharges at the stations of Itapeuá, Manacapuru and Jatuarana were above average through July 1998. By August 1997, all three stations showed a quite rapid recession, recording discharges increasingly lower than the mean. Minimum discharges at Itapeuá were recorded during October 1997, while in Mancapuru and Jatuarana the minima were observed during November 1997. It is interesting to note that the differences between the discharges and the mean during the recession increased downstream, indicating the existent of increasingly larger discharge deficits along the main-stem. Therefore, discharges in the middle Amazon were above the mean during the first half of 1997, and then began a strong recession.

Finally Óbidos, at the lower Amazon Basin, showed a consistent behaviour with the values observed in the stations located in the middle Amazon Basin: discharges

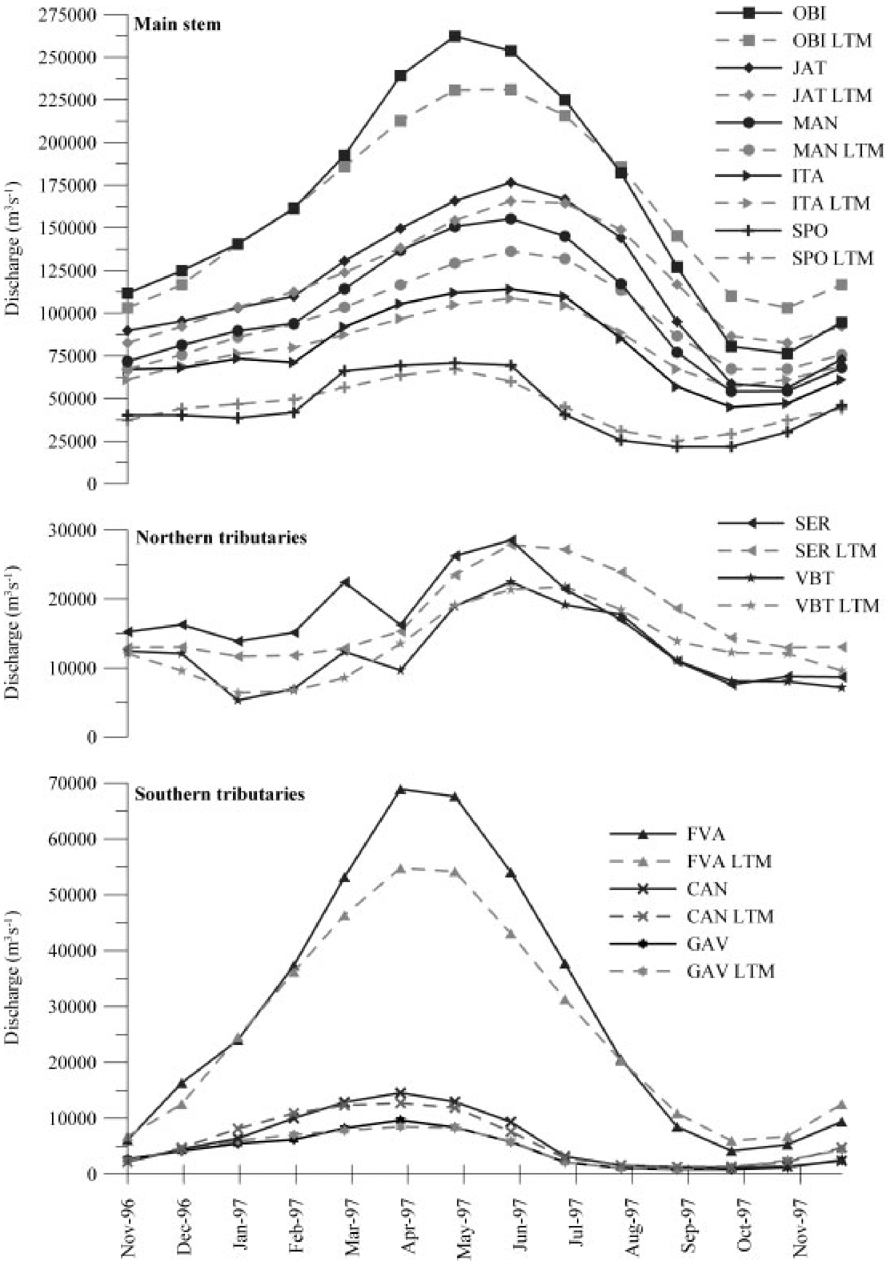

Figure 4. Amazon and main tributaries river discharges during the 1996–1997 drought. Main-stem discharge stations include São Paulo de Olivença (SPO), Itapeuá (ITA), Manacapuru (MAN), Jatuarana (JAT) and Óbidos (OBI). Northern tributaries discharge stations are Vila Bittencourt (VBT) on the Japurá River, and Serrinha (SER) on the Negro River. Among the southern tributaries, discharge stations are Gavião (GAV) on the Juruá River; Canutama (CAN) on the Purus and Fazenda Vista Alegre (FVA) on the Madeira River. LTM indicates the long-term mean (1978–1996) of the corresponding discharge station

close to the mean during the rising water period, above the mean at the peak and a strong recession with discharges below the mean from August 1997 onwards. The differences between discharges and the mean were larger in October 1997, when the values were minimum.

Figure 4 also shows the time variation of river discharges along some tributaries. The Gavião station, located in the Juruá River, presented discharges close to the mean until February 1997, above the mean during high water and close to the mean during most of the recession. Only by October 1997, water discharges became lower than the mean. In Vila Bittencourt station, in the Japurá River, discharges oscillated around the mean during the first half of 1997. During the second half of 1997, discharges became significantly lower than the mean, and a large deficit was observed by October 1997. The Purus River in Canutama showed almost the same behaviour as the Juruá River: discharges close to the mean during the rising period and most of the recession, above the mean during high water, and below the mean past October 1997.

The Negro River in Serrinha presented discharges above the mean until June 1997, and then discharges remained significantly below the mean. Since the Negro River contribution to the Solimões River reaches its maximum in June, when the Amazon River in Óbidos

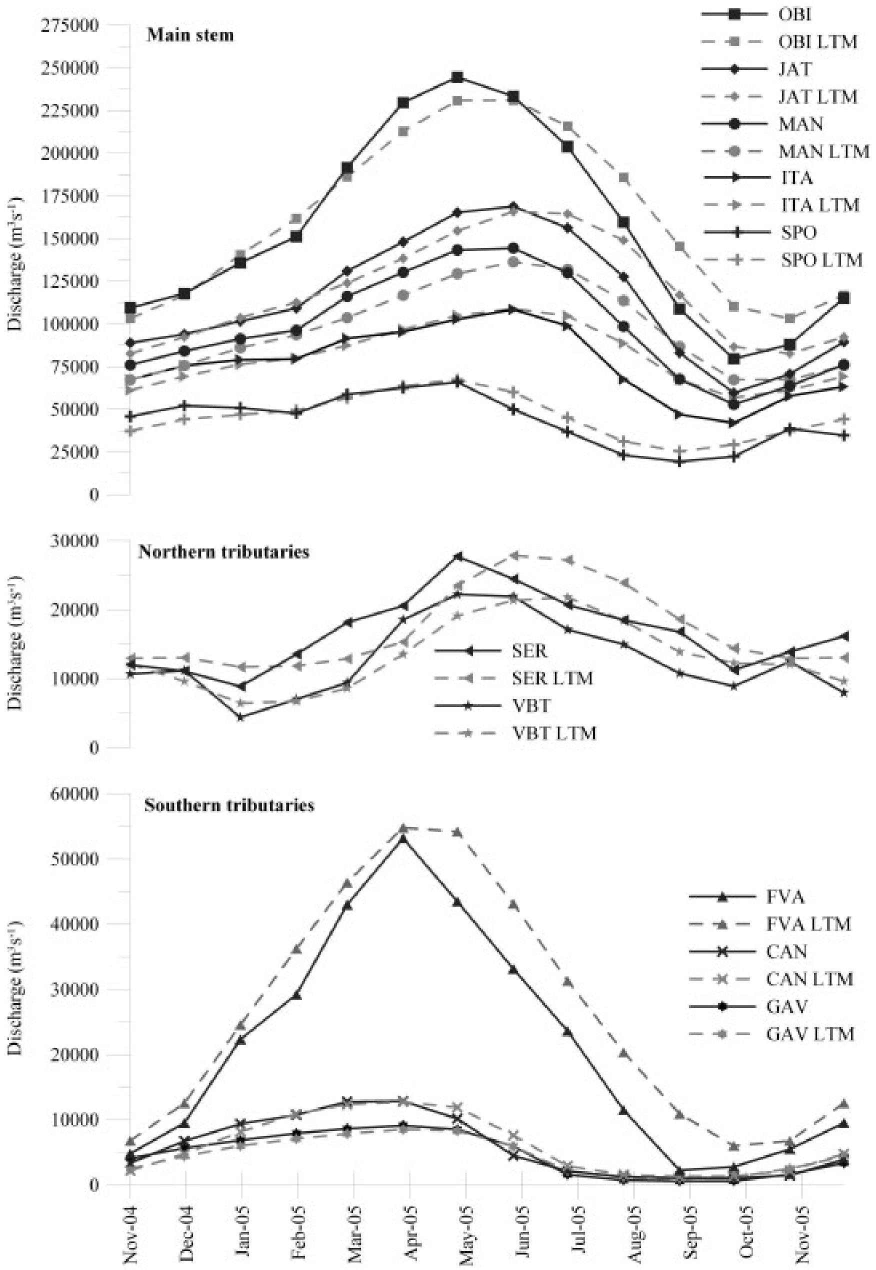

Figure 5. Amazon and main tributaries river discharges during the 2004–2005 drought. Main-stem discharge stations include São Paulo de Olivença (SPO), Itapeuá (ITA), Manacapuru (MAN), Jatuarana (JAT) and Óbidos (OBI). Northern tributaries discharge stations are Vila Bittencourt (VBT) on the Japurá River and Serrinha (SER) on the Negro River. Among the southern tributaries, discharge stations are Gavião (GAV) on the Juruá River; Canutama (CAN) on the Purus and Fazenda Vista Alegre (FVA) on the Madeira River. LTM indicates the long-term mean (1978–1996) of the corresponding discharge station

is already in recession, it is important to note that Negro River contribution affects the shape of the recession of the main-stem. Finally, the Madeira River at Fazenda Vista Alegre station showed discharges close to the mean during the first part of the rising water period, while discharges were well above the mean during the high water season. Differences were reduced during the recession, and by September 1997, discharges became slightly below the mean.

As shown in Figure 5, the drought of 2004–2005 had very distinctive features compared to the 1996–1997 event: along the main-stem (stations São Paulo de Olivença, Itapeuá, Manacapurú, Jatuarana and Óbidos), the discharges recorded in 2005 were close to the mean during the rising water period and consistently above the mean at the peak discharge.

By April 2005, the discharge in São Paulo de Olivença became lower than mean and remained below the mean for the whole low water period, which coincides with the intensification of negative rainfall anomalies (Marengo *et al.*, 2008a).

In Itapeuá, Manacapurú and Jatuarana, in the middle Amazon River, the discharges during 2005 remained close (in Itapeuá) or above (in the other stations) the mean through June 2005, then a steep recession ensued, which reached a minimum in October 2005. Óbidos (lower Amazon) showed a similar behaviour. Similar to what was observed in 1996–1997, discharges deficits increased downstream, indicating that the signal of the drought was amplified along the river course.

In the tributaries, differences between discharges in 2005 and the mean varied. The Gavião station, in the Juruá River, showed discharges above the mean during the high water season and through most of the recession period. Vila Bittencourt, on the Japurá River, recorded values above the mean until June 2005, and then discharges dropped below the mean during the whole recession. Canutama, in the Purus River, has a similar behaviour, except that the values below the mean were observed earlier, in April 2005. In the Negro River in Serrinha, meanwhile, values remained above the mean through May 2006, and then consistently below the mean. Finally, in Fazenda Vista Alegre in the Madeira River, values were slightly below the mean until April 2005, and then rapidly decreased with values significantly below the mean to the minimum recorded in September 2005.

Comparison of the 1996–1997 and the 2004–2005 droughts indicates important differences between both events. During 1996–1997 El Niño-related drought, discharges were close or slightly above the mean during the first half of 1997, and became below the mean between July and August 1997. The strong recession observed in 1996–1997 is explained by the combination of the contribution of northern and southern tributaries: both the Negro and the Japurá rivers had discharges significantly below the mean since June 1997 and during the whole recession period. In spite of this, discharges remained above the mean until July 1997 in the main-stem, clearly influenced by the southern tributaries (where discharges remained above the mean until July 1997). As recession proceeded, discharges in the southern tributaries became closer to the mean, and the strong deficits observed in northern tributaries eventually affected the discharges in the main-stem, causing a rapid drop in water levels to the minimum of October 1997.

The drought of 2004–2005 presented discharges along the main river course close or even above the mean during the rising water period, with peaks slightly greater than the mean. Soon after the peak discharge, recession began rapidly and with increasing rate, resulting in a minimum value at Óbidos station slightly above than those of the drought of 1996–1997. During 2004–2005, discharges became significantly below the mean by July 2005 about 2 months earlier than 1996–1997 drought (considering that discharges in the main-stem were only slightly below the mean during August 1997), and finished 1 month earlier than in 1996–1997. Therefore, the recession during the 2004–2005 drought lasted longer, but it was smoother than the recession during the 1996–1997 event.

This behaviour is consistent with the observed river discharges in most tributaries. The discharges were in general above or close to the mean discharge during the rising water period. Because the tributaries have larger-than-normal discharges through middle 2005, discharges along the main river were accounted for this behaviour. After the peak discharge, most of the tributaries showed a steep recession with discharges significantly below the mean, clearly associated with the intensification of negative rainfall anomalies of the second quarter of 2005. The same hydrological behaviour was also verified in the Negro River, which drains an area of the basin outside the region mostly affected by rainfall deficits. Discharges lower than the mean in the Negro are consistent with rainfall anomalies, which were 10–20% below the mean between December 2004 and February 2005 and between normal to 10% above normal from March to May 2005 (Marengo *et al.*, 2008a).

Therefore, during the 1996–1997 drought, discharges deficits along the main-stem were controlled most of the time by northern tributaries, and the rate of fall of river discharges were smoothed during the first part of the recession because southern tributaries contributed to higher-than-normal discharges during the high water season. During the 2004–2005 drought, on the other hand, the signal observed in the main-stem was controlled mostly by discharge deficits of southern and western tributaries, while the northern tributaries had a secondary role, which is exactly the opposite of what was seen during the 1996–1997 El Niño-related episode. In 2004–2005, the discharge in northern tributaries peaked earlier, and almost all tributaries initiated simultaneously a rapid recession, accelerating the falling of river stages in the main-stem, which result in a strong recession with river stages as low as those observed in 1996–1997. The comparison of annual minimum monthly discharges (Table III) during both episodes indicates that, along the main-stem, the 2004–2005 drought affected more strongly the main-stem upstream of the Negro–Solimões river confluence (stations São Paulo de Olivença, Itapeuá and Manacapurú), while the effect of the 1996–1997 drought was more severe downstream the confluence (Jatuarana and Óbidos). This indicates that the role of the Negro River was crucial to explain the minimum recorded in 1996–1997.

Moreover, the comparison of the minimum discharges during both episodes indicates that discharges were about 10% lower during 2004–2005 compared to 1996–1997 in the upper Amazon River (São Paulo Olivença station), and this difference gradually decreased downstream to become lower for the 1996–1997 episode downstream of the Negro–Solimões River confluence.

Table III also shows that the minimum discharges recorded in the southern tributaries, at the stations of Gavião (Juruá River), Canutama (Purus River) and Fazenda Vista Alegre (Madeira River) during 2004–2005, were lower than the minimum discharges recorded during 1996–1997. In northern tributaries, exactly the opposite occurred: the annual monthly minimum discharges at the stations of Vila Bittencourt (Japurá River) and Serrinha (Negro River) during 1996–1997 were below those of 2004–2005. This difference is reinforcing the conclusion that the 1996–1997 drought was controlled by northern

Table III. Annual minimum monthly discharge during the 1997 and 2005 droughts for the representative stations, including the month where the minimum was observed, and the percentage of the minimum relative to 1978–2006 long-term mean of the corresponding month (% LTM)

Code	Station	1997			2005		
		Annual monthly minimum discharge	Month	% LTM	Annual monthly minimum discharge	Month	% LTM
		Main-stem					
SPO	São Paulo de Olivença	21 755	Sep	86·0	19 327·2	Sep	76·4
ITA	Itapeuã	45 051·3	Oct	79·4	41 973·5	Oct	73·9
MAN	Manacapuru	54 124·0	Oct	80·4	52 780·4	Oct	78·4
JAT	Jatuarana	67 226·1	Nov	68·2	59 543·9	Oct	72·1
OBI	Óbidos	76 394·0	Nov	74·1	79 477·1	Oct	77·1
		Main tributaries					
GAV	Gavião	877·3	Sep	91·9	574·2	Sep	60·1
VBT	Vila Bittencourt	7179·0	Dec	74·7	7964·9	Dec	82·8
CAN	Canutama	1205·5	Oct	87·6	1034·3	Oct	75·1
SER	Serrinha	7626·5	Oct	53·0	11 258·2	Oct	78·3
FVA	Fazenda Vista Alegre	4182·3	Oct	69·7	2247·6	Sep	37·4

tributaries, while the 2004–2005 drought was driven by southern tributaries.

Another important difference between the two droughts is related to the timing of peak discharges of the tributaries in 2004–2005. In normal years, highest stages in the Madeira River occur 2 to 3 months prior to those in the Negro River, and the time displacement between the peaks is fundamental for damping the extremes along the main-stem because the Negro River is still rising when the Madeira River is already receding (Meade *et al.*, 1991). Different contribution times of the Amazon tributaries is one of the reason why the Amazon flood wave is subcritical and diffusive in character; with deep and relatively slow moving flow which occurs at very low surface slopes (Trigg *et al.* 2009), making backwater effects significant either in high or low waters. Moreover, backwater effects are significant all along the middle and lower Amazon main-stem, as well as in the tributaries close to their confluence with the main-stem (Meade *et al.*, 1991; Filizola *et al.*, 2009).

Comparison between Figures 4 and 5 reveals that during 1996–1997, the Madeira River at Fazenda Vista Alegre station peaked 2 months earlier than the Negro River at Serrinha station. During 2004–2005, on the other hand, peak time difference was reduced to a month because the Negro River at Serrinha peaked earlier than normal, and the recession in all tributaries began almost simultaneously. Besides this, water levels were well below normal in the Madeira River during 2004–2005, which favour the occurrence of higher surface water gradients along the Amazon main-stem since the mouth of the Madeira River is located downstream the Negro River confluence. The combination of both effects is the most likely explanation to the fact that water levels in the main-stem dropped so fast during 2005.

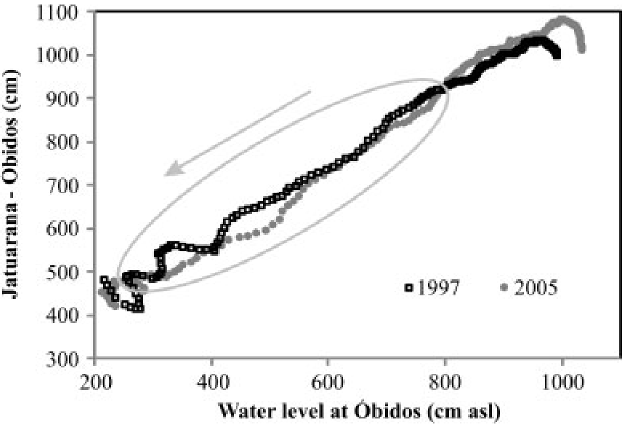

Figure 6. Water levels daily differences between Jatuarana and Óbidos stations plotted against water level at Óbidos, during the main-stem recessions of 1997 (16 May 1997–09 November 1997) and 2005 (19 May 2005–27 October 2005). The arrow indicates the timeline, while the ellipse highlights the main differences between both events

This effect is illustrated in Figure 6, which presents the difference between daily water level above sea level (asl) at Óbidos station (downstream the mouth of the Madeira River) minus water levels at Jatuarana station (located immediately downstream the Negro–Solimões rivers confluence); plotted against the water levels at Óbidos, for the whole recession of 1997 and 2005. The altitude of the zeros of the discharge stations was extracted from Kosuth *et al.* (2006). The difference in water level of both stations is an indicator of mean energy gradients in the main-stem and consequently, the influence of backwater effects on discharges.

Figure 6 shows that the 1996–1997 drought presented higher gradients compared to the 2004–2005 event at the beginning of the recession (when water stages were higher than 800 cm asl at Óbidos). This is related to two different factors: (i) the 1996–1997 high water period was higher in magnitude (Figure 4), particularly close to Negro River, which favour the occurrence of steeper water level gradients at the flood period; (ii) as mentioned before, the peaks of the Negro and Madeira rivers were 2 months time-lagged during 1997 (Figure 4), and only 1 month in 2005 (Figure 5). It is obvious that the closer the peaks of both rivers, the lesser the differences in water levels between Jatuarana and Óbidos stations at high waters.

As recession proceeded, and when water levels at Óbidos decline below 800 cm asl, differences in water levels between Jatuarana and Óbidos, for the same water level at Óbidos station, were consistently higher during 2005 compared to 1997. This coincides with below normal discharges of the Madeira River (see stations Fazenda Vista Alegre in Figure 5). It is clear that the lower-than-normal water levels at Óbidos increased the main-stem gradients and accelerated river recessions. The difference between water levels of both stations were sometimes 60 cm higher during 2004–2005 compared to 1996–1997. Since the distance between Jatuarana and Óbidos stations is about 510 km (Table II), it may be argued that the differences between water levels during both drought events were not significant enough to cause substantial impacts on discharges. However, hydraulic dictates that gradients vary in a nonlinear way between both stations, and given the hydrological conditions prevailing during the recession of 2005, gradients differences among both events should have been minimum close to Jatuarana and gradually increased to a maximum at the Madeira River mouth. Therefore, Figure 6 depicts the mean difference between Jatuarana and Óbidos and smooths the variability in between.

Finally, at the end of the recession stage (below 300 cm asl at Óbidos), differences tend to be mixed, since water levels become very sensitive to local rainfall.

Analysis of incremental discharges along the main-stem of the Amazon River

In order to understand why the drought of 2004–2005 had such a severe hydrological impact, although it was geographically constrained in terms of rainfall anomalies, incremental discharges along the main-stem were analysed. Figure 7 compares the behaviour of river discharges for the 1996–1997 and 2004–2005 droughts, and the mean for the period 1978–2006, in the upper basin (São Paulo de Olivença station), the incremental discharges in the middle river basin (indicated as São Paulo de Olivença—Itapeuá, Itapeuá-Manacapurú, Manacapurú—Jatuarana, Jatuarana—Óbidos) and finally in Óbidos (lower Amazon).

Between São Paulo de Olivença and Itapeuá, discharges during 1996–1997 were close to the mean during the rising of water levels and above the mean during the high water season. By September 1997, the discharge became lower than the mean and remained so for the rest of the year. The largest discharge deficits were recorded in December 1997. Similarly, during 2004–2005, discharges during the rising water period were close to the mean and above the mean at the peak. However, a strong recession began after the peak. Discharge deficits increased through October and had disappeared by December 2005. The main-stem between São Paulo de Olivença and Itapeuá receives the contribution of the Juruá River (that drain the southwestern part of the basin) and the Japurá (that drains the Colombian Amazon). The difference between both episodes is that discharge deficits continued after December 1997, while there is a clear recovery after November 2005.

Between Itapeuá and Manacapurú, both events (1996–1997 and 2004–2005) presented a similar behaviour: discharges were significantly above the mean in the rising period, which explains why discharges were above the mean at the beginning of both 1997 and 2005 along the main-stem; and were slightly below-the-mean discharges at the recession. The most important tributary of this part of the main-stem is the Purus River which showed, at Gavião station, above-normal discharges during the high waters and below-average discharges at the end the recession period during both drought episodes.

Between Manacapurú and Jatuarana, the main tributary is the Negro River. Figure 7 indicates that river discharges were below the mean all the time both in 1996–1997 and 2004–2005. Discharges during the drought of 1996–1997 were higher through March 1997 than those of 2005 and then became lower. There were important differences in discharges past October 1997 in comparison to 2005: in the former, discharges were significantly low from October to December; in the latter, discharges recovered in November and December. Obviously, this is related to the fact that El Niño event of 1997–1998 remained active until May 1998.

Figure 7 suggests that discharges deficiencies in the Negro River during both droughts have clearly influenced the shape of the hydrograph of the main river. Moreover, the minimum discharges recorded between Jatuarana and Manacapurú in November 1997 explain the minimum discharges of the drought of 1996–1997 along the main-stem. As shown in Figures 4 and 5, discharges at Serrinha station were above the mean in the first half of 1997, and from February to June 2005, in opposition to what was observed between Manacapurú and Jatuarana (Figure 7), where discharges were below the mean throughout the period. A possible explanation for this apparent inconsistent behaviour could be related to the fact that Serrinha station captures only 60% (Table II) of the signal of the Negro Basin. It should be noted that gauging stations downstream Serrinha are affected by substantial backwater effects, since Negro River stages closer to the confluence with the Solimões River are, most of the time, controlled by Solimões River variations (Filizola *et al.*, 2009). In spite of this limitation, additional evidences of the spatial distribution of discharges deficits are provided by satellite gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) for the 2005 drought (Chen *et al.*, 2009). GRACE estimations indicated that the area affected by water storage deficits between August and September 2005, compared to the average GRACE water storage between 2002 and 2007, includes the lower Negro River Basin downstream Serrinha station. This suggests that discharges deficits increased downstream at the lower Negro Basin in 2004–2005, in agreement with Figure 7. Since the

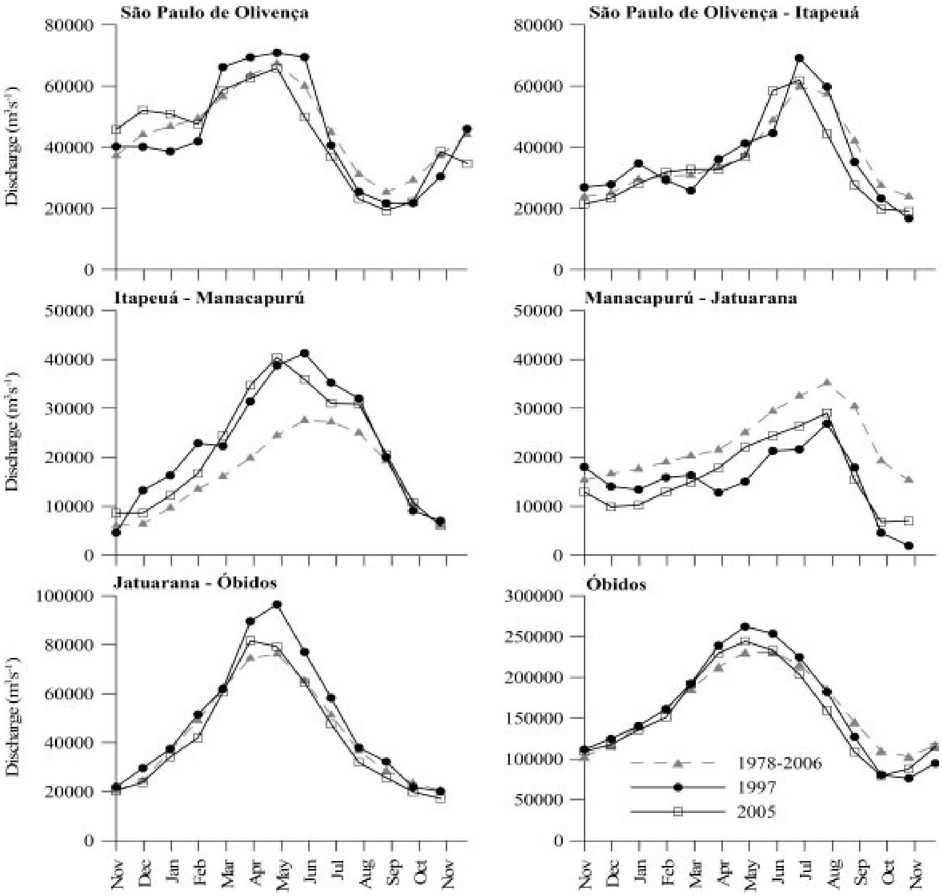

Figure 7. Comparison of discharges in the upper (São Paulo de Olivença) Amazon, incremental discharges in the middle Amazon (indicated as São Paulo de Olivença—Itapeuá, Itapeuá—Mancapuru, Manacapuru—Jatuarana, Jaturana—Óbidos), and finally discharges in the lower Amazon (Óbidos) for the 1997–1998 and 2004–2005 droughts. Black circles indicate the 1997–1998 drought, open squares indicate the 2004–2005 episodes, and the grey triangles correspond to the mean between 1978 and 2006

1996–97 drought impacted more severely northern tributaries, it is likely to assume that it was also the case during this drought, before GRACE became operational.

Between Jatuarana and Óbidos, differences between the events of 1996–1997 and 2004–2005 were observed. During 1996–1997, river discharges were well above the mean during high water (April–June). During recession, discharges gradually became close to the mean and slightly below the mean by late 1997. During 2004–2005, however, discharges were slightly above the mean during high water and became below the mean from June 2005 onwards. As already verified in other rivers sections, during 2005 there is a recovery of discharges in December, which is clearly not the case for December 1997. Most of the signal at this part of the river is modulated by the Madeira Basin, with a minor contribution of the Trombetas River (draining central–northern Amazon). This behaviour is consistent with the hydrograph of the Madeira River at Fazenda Vista Alegre station.

This analysis showed that the event of 1996–1997 extended beyond December 1997, in agreement with the continuation of the effects of El Niño episode of 1997–1998. The event of 2005, on the other hand, began to dissipate by November 2005. This difference in behaviour is important to explain why minimum discharges during 1996–1997 occurred during November and were lower than those recorded in 2005. In the 2004–2005 drought, there was a recovery in the discharges on most tributaries by November 2005, which explain why the minimum discharges were observed in October.

As a conclusion of this section, the analysis of incremental discharges revealed that discharges deficits were more intense between Manacapurú and Jatuarana (where the Negro River contributes) during the 1996–1997 drought. Meanwhile, during the 2004–2005 episode, discharge deficits were larger between São Paulo de Olivença and Itapeuá (where the Japurá and the Juruá rivers contribute to the main-stem) and between Jatuarana and Óbidos (where the most important contribution comes from the Madeira River).

CONCLUSIONS

The analysis of the hydrographs along the main-stem and in individual tributaries indicates that the drought of 1996–1997 was mostly controlled by tributaries draining the northern part of the basin, while the 2004–2005 event was controlled by southwestern tributaries.

In the drought of 1996–1997, discharges were close to the mean during early 1997, became well above the mean during the high water and drastically dropped after July 1997, producing very low discharges during November 1997. Lower-than-normal discharges continue well beyond 1997.

In the drought of 2004–2005, on the other hand, tributaries that drain the northern part of the basin peaked earlier than 'normal' and then initiated a rapid recession, almost simultaneously with a strong recession of southern tributaries which were affected by below-the-mean discharges. This combination heavily impacted the main-stem because it also increased water level slopes in the main-stem, causing a rapid decline of river stages. In comparison with the drought of 1996–1997, river discharges during 2004–2005 remained below mean values for a longer period. Although the 2004–2005 drought was not geographically extensive in terms of negative rainfall anomalies as an El Niño-type event, river discharges were as low as those recorded during 1996–1997.

From a hydrological point of view, the analysis of both droughts revealed that the Amazon River, with a complex network of tributaries subjected to different climate regimes, with diffusive river flows strongly dependent on backwater effects either in high or low waters (Trigg *et al.*, 2009); regionally restricted negative rainfall anomalies can have a stronger impact downstream than more geographically extensive droughts, provided that rainfall deficiencies occur on critical time during the main-stem recession.

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