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The flood recession period in Western Amazonia and its variability during the 1985–2015 period

Josyane Ronchail[a,b,*], Jhan Carlo Espinoza[c], Guillaume Drapeau[a,d], Manon Sabot[e], Gérard Cochonneau[f], Tatiana Schor[g]

[a] Université Paris-Diderot, Sorbonne Paris Cité, Bâtiment Olympe de Gouges, Place Paul Ricoeur, 75013 Paris, Case courrier 7001, 75205 Paris Cedex 13, France
[b] Laboratoire d'Océanographie et du Climat (LOCEAN, Sorbonne Universités-UPMC, CNRS, IRD, MNHN), 4 Place Jussieu, 75252 Paris Cedex 05, Paris, France
[c] Instituto Geofísico del Perú (IGP), Calle Badajoz #169, Mayorazgo IV Etapa, Ate Vitarte, Lima, Peru
[d] Pôle de Recherche pour l'Organisation et la Diffusion de l'Information Géographique (PRODIG), 2 rue Valette, 75005 Paris, France
[e] Université Pierre et Marie Curie, Sorbonne Universités, 4 Place Jussieu, 75252 Paris Cedex 05, Paris, France
[f] Institut de Recherche pour le Développement (IRD), Casilla Postal 18-1209, Lima 18, Peru
[g] Universidade Federal do Amazonas (UFAM) and Núcleo de Estudos e Pesquisas das Cidades na Amazônia Brasileira (NEPECAB), Av. General Rodrigo ¡Octávio, 6200, Coroado I, Cep: 69080-900, Manaus, Brazil

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ABSTRACT

Study region: The upper Amazon River, where the water level measured at the Tamshiyacu station (Peru) shows seasonal variability of seven meters.

Study focus: Key parameters for the flood recession period (beginning, end and duration of the low-water period, velocity of water falling and rising, and inversions in the direction of stage change known as "repiquete" events) are analyzed for the period 1985–2015, along with their relationship to rainfall integrated in the upper Amazon basin at Tamshiyacu.

New hydrological insights: The low-water period lasts about four months, beginning, on average, at the end of July and ending in early November. Since the late 1990s, the low-water period has tended to end later, last longer and the flood recession ends more abruptly than it used to. This may be related to the increased frequency of dry days during the austral winter in the central and southern part of the basin and to increased and more intense rainfall in late spring (November–December). Repiquete events are frequent, 8 each year on average, and sometimes very acute: 18 events with a water-level reversal greater than one meter were registered during the 1985–2015 period. They are related to unusual, intense and extended rainfall during the week preceding the repiquete. Extensions of this preliminary work are suggested, as well as possible implications for recessional agriculture.

1. Introduction

While hydroclimatic extremes have been carefully studied in the Amazon basin (Callede et al., 2004; Marengo and Espinoza, 2015; Marengo et al., 2008, 2013; Zeng et al., 2008; Chen et al., 2010; Espinoza et al., 2011, 2013, 2014; Satyamurty et al., 2013; Molina-Carpio et al., 2017), there has been little study of the annual water-level cycle of the Amazon River. In the western Amazon,

* Corresponding author at: Université Paris-Diderot, UFR GHES, Bâtiment Olympe de Gouges, Case courrier 7001, 8 rue Albert Einstein, 75205 Paris Cedex 13, France.

E-mail address: josyane.ronchail@locean-ipsl.upmc.fr (J. Ronchail).

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precipitation is highly variable, with a rainy season in the austral summer, which is related to the onset of the South American Monsoon System and the translation of convergence in the southern hemisphere, and a drier season in the austral winter, related to their retreat (Zhou and Lau, 1998; Vera et al., 2006). This rainfall seasonality causes a seven-meter fluctuation between low- and high-water stages of the Amazon River at the Tamshiyacu station (Peru), upstream from Iquitos. This study focuses on the flood recession period, which is characterized by the decrease of the water level.

This period of the year is of particular interest for local food security and economic activity in the region. The fertile riverbanks and floodplains ("varzeas"), which are flooded during the high-water period, are exposed during the flood recession period (Junk, 1982; Junk and Furch, 1993) making them available for recessional agriculture during those months (Hiraoka, 1985; Bahri, 1993; Noda, 2007; Kvist and Nebel, 2001; Adams et al., 2005). Moreover, food prices are lower when the varzeas are producing (Moraes and Schor, 2010). When the average cycle is perturbed, for example when the duration of the recession is too short for plants to mature or when the onset of the rainy season and rising water occur very suddenly, crops may be lost (Kvist and Nebel, 2001; Labarta et al., 2007; Drapeau et al., 2011; Hofmeijer et al., 2013; Pinho et al., 2015; Sherman et al., 2015; MINAG, 2011, 2013). Food security may then be affected, despite the tradition of diversifying the landscape and the location of cultivated plots and of taking advantage of multiple habitats (Pinedo-Vasquez et al., 2002; Arce-Nazario, 2011). The importance of unexpected stage reversals ("repiquetes") on the rice-planting strategies of farmers near Iquitos has been described by various authors (see for instance Hiraoka, 1985; Rios Arevalo, 2005), and the associated high risk of crop loss due to this natural hazard has been assessed by Coomes et al. (2016), List (2016) and List and Coomes (2017). Water-level variations strongly affect not only production, but also the transportation of produce as both transportation time and distance significantly increase during the flood recession period (Tenkanen et al., 2015). This topic is an important variable in cash-crops for local markets (Hiraoka, 1985).

Local biota has developed specific adaptations that enable it to live in constantly changing physical conditions, either aquatic or terrestrial, depending on the season (Junk, 1982). Despite these adaptations, losses are high, especially when extreme water levels are observed during the high- or low-water season. Fish, game and fruit are important components of the local diet, and shortages can affect both local food security and cash-crop systems (Takasaki et al., 2004; Nascimento, 2017). Variations in water level also have an important impact on the quantity and quality of water available to the local population (Cidade, 2017), which affects health and quality of life.

Analysis of the flood recession period is also of particular interest because the annual rainfall cycle has changed in recent decades in the Amazon basin. Longer dry seasons have been observed since the 1980s, particularly in the southern Amazon, with later onsets and earlier ends of the wet season (Li and Fu, 2006; Carvalho et al., 2011; Marengo et al., 2011; Dubreuil et al., 2012; Fu et al., 2013; Yin et al., 2014; Arias et al., 2015; Debortoli et al., 2015; Espinoza et al., 2016). This may be related to changes in convection due to deforestation and modifications in regional circulation (Li and Fu, 2006; Yin et al., 2014; Arias et al., 2015; Wright et al., 2017). Fernandes et al. (2015) also suggest the existence of a decadal variability in western Amazon rainfall related to the decadal variability in tropical Atlantic Ocean sea surface temperature (SST).

Corresponding to these changes, a significant decrease in rainfall during the dry season has been documented in the upper Amazon basin since the 1970s (Espinoza et al., 2006, 2011), including an increase in the frequency of dry days since 1986 (Espinoza et al., 2016). Hydrological conditions are expected to change further with climate change. Rainfall is projected to increase in western Amazonia during the wet season, contributing to augmented mean and maximum discharge in large rivers draining the Andes (Guimberteau et al., 2013; Boisier et al., 2015; Zulkalfi et al., 2016). These changes would lead to an average increase of three months in the duration of inundation by the end of the 21st century (Langerwisch et al., 2013) and to more widespread flooding over Peruvian floodplains in western Amazonia (Sorribas et al., 2016).

This paper is a contribution to the analysis of key parameters of the flood recession period (dates of beginning and end of the low-water period, duration of the low-water period, speed of water falling and rising, occurrence of repiquetes) in the upper Amazon basin at the Tamshiyacu station and their evolution during the 1985–2015 period. Section 2 describes the data and methodologies on which this study is based. Section 3 describes the time evolution of the main parameters of the flood recession period. They will be related to rainfall averaged in the upper Amazon basin at Tamshiyacu and to the frequency of dry and wet days in this basin. Results are synthetized in Section 4 and extensions of this preliminary work are suggested.

2. Data and methods

2.1. Data

The National Meteorology and Hydrology Service of Peru (SENAMHI) provided high-quality daily water level data for the Amazon River at Tamshiyacu (Fig. 1b). These data are gathered by the National Observation Service SNO-HYBAM "Geodynamical, hydrological and biogeochemical control of erosion/alteration and material transport in the Amazon, Orinoco and Congo basins." Daily water level values are available as of 1985. SNO-HYBAM also provided Hybam Observed Precipitation data (HOP), a gridded dataset for the entire Amazon basin derived from 752 meteorological stations in five countries (Espinoza et al., 2009a). Data are collected by the national institutions in charge of hydro-meteorological monitoring: National Agency of Water (ANA) in Brazil; SENAMHI in Peru and Bolivia; the National Meteorology and Hydrology Institute (INAMHI) in Ecuador; and the Hydrology, Meteorology, and Environmental Studies Institute (IDEAM) in Colombia. The HOP dataset is available from 1980 to 2009 on a daily time step and a 1°x1° grid (Guimberteau et al., 2012). In the Peruvian-Ecuadorian Amazon basin, delimited by the Tamshiyacu hydrological station, basin-integrated rainfall is computed from 234 meteorological stations from the HOP dataset (Espinoza et al., 2011). For more details about quality control of rainfall data and geostatistical interpolation of rainfall observations, see Guimberteau et al. (2012). Gridded HOP

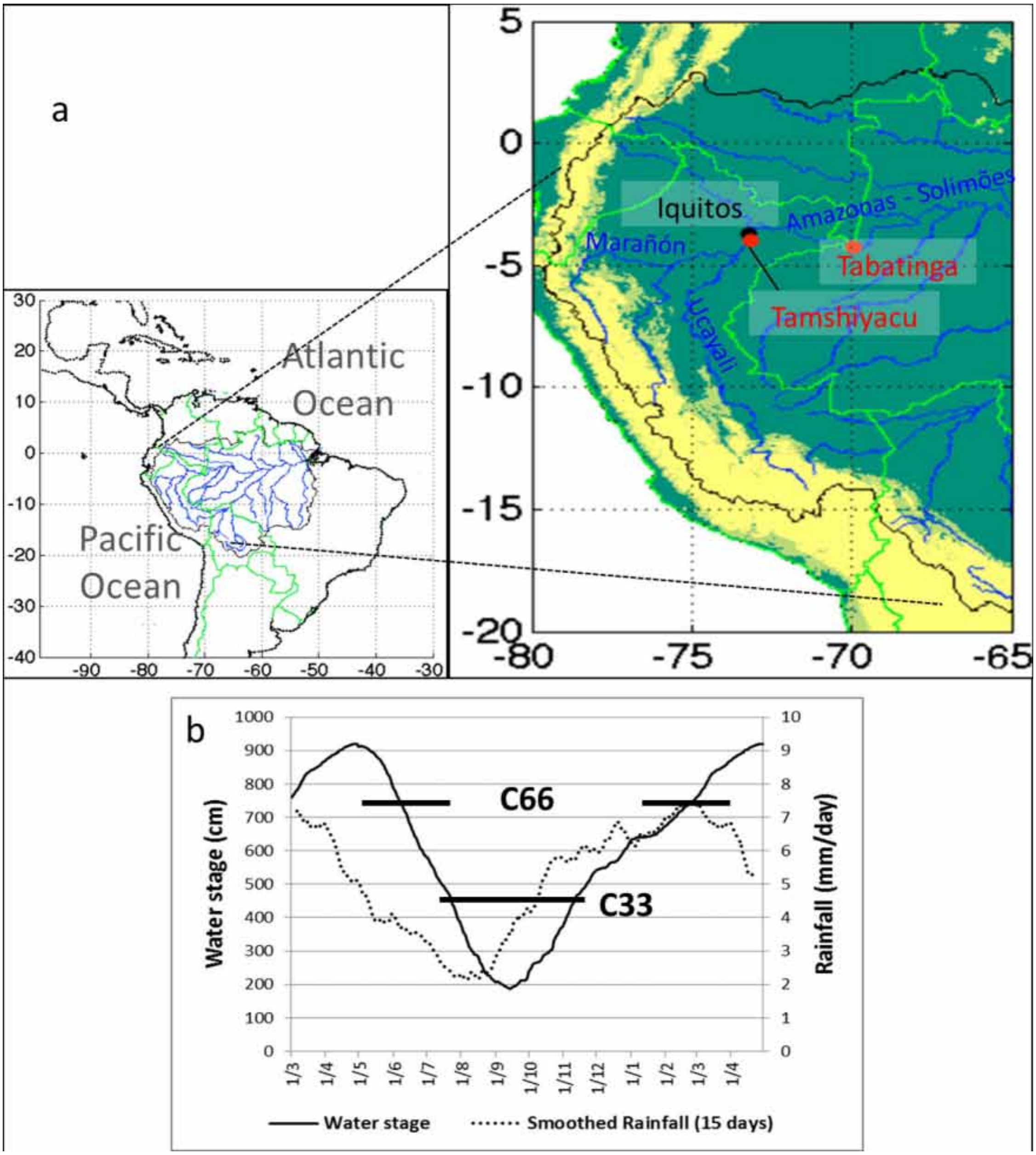

Fig. 1. a) Location of Tamshiyacu hydrological station and main rivers, b) Mean water stage cycle (cm, plain line) at Tamshiyacu station (May–April 1985–86 to 2014–15) and mean basin-integrated and 15-day smoothed rainfall (in mm/day, dotted line) in upper Amazon basin at Tamshiyacu (March–February 1985–86 to 2008–09). Positions of 20th, 33rd and 66th centiles of the water stage are indicated.

daily data are freely available in NetCDF format at www.so-hybam.org.

Over the upper Amazon basin at Tamshiyacu, monthly wet-day frequency (WDF) is defined as the frequency of days with rainfall greater than 10 mm, which is about twice the mean annual rainfall in the basin (estimated at 4.8 mm/day; Espinoza et al., 2011). Monthly dry-day frequency (DDF) is defined as the frequency of days with rainfall less than 1 mm (Espinoza et al., 2016). These data are derived from HOP.

2.2. Definition of the flood recession parameters in the upper Amazon basin at Tamshiyacu

The Amazon River up to the Tamshiyacu station (the first gauging station downstream from the confluence of the Marañón and Ucayali rivers; Fig. 1a) has a huge drainage (750 000 km^2), half of which is in the Andes above 500 m (Fig. 1a). The long-term mean discharge at Tamshiyacu is 32 000 m^3/s, about 16% of the Amazon discharge at the estuary (Espinoza et al., 2006, 2009b).

Table 1

Main characteristics (average, minimum, maximum, dates of occurrence or number of days, trend, presence of a break in the time series, and averages before and after the break (except in c) of a) the dates of the first and second C33 and C66, b) the durations of the periods between the first and second C33 and C66, and c) the durations of water level fall (first C66 to first C33) and rise (second C33 to second C66) after the flood recession period. * Indicates a break in 1998, ** indicates a break in 1994, and *** indicates no break in the time series. Empty boxes indicate the absence of a trend.

a	Mean date	Earliest date	Latest date	Standard Deviation	Trend: BP and probability	Trend: Spearman and probab.	Mean for the period 1985–1998*	Mean of the period 1999–2015
C33 (4.5 m) beginning	20/7	20/6	24/8	17				
C33 end	11/11	25/9	2/2	24	0.49 ($p < 0{,}01$)	0.51 ($p < 0{,}01$)	25-oct.	26-nov.
C66 (7.3 m) beginning	13/6	7/5	21/7	20				
C66 end	19/1	14/11	20/3	33				

b	Mean number of days	Minimum	Maximum	Standard Deviation	Trend: r and probability	Trend: Spearman and probab.	Mean for the period 1985–1994**	Mean of the period 1994–2015
Duration C33	114	73	225	30	0.39 ($p < 0{,}05$)	0.39 ($p < 0{,}05$)	93	125
Duration C66	220	141	290	40				

c	Mean number of days	Minimum	Maximum	Standard Deviation	Trend: r and probability	Trend: Spearmann and probab.	Mean for the period 1985–1995***	Mean of the period 2005–2015
Duration C66-C33	38	12	85	18		0.34 ($p < 0{,}1$)	31	41
Duration C33-C66	70	20	149	35	0.47 ($p < 0{,}01$)	0.44 ($p < 0{,}02$)	82	51

Fig. 1b shows the average annual cycles of basin-averaged rainfall and water level at Tamshiyacu from May, when the highest water-level values are observed, to April. Rainfall peaks at the end of February (about 7,5 mm/day) and the lowest amounts are observed in August (about 2 mm/day). Accordingly with the 2-months lag between rainfall and discharge in this basin (Espinoza et al., 2006, 2011), the peak water level occurs at the very beginning of May (9.2 m) and the lowest level in mid-September (1.9 m). The range between the two levels is about 7.3 m. The water recedes rapidly, as the dry season starts concomitantly in most of the sub-basins of the upper Amazon basin (Fig. 1b). In contrast, the water rises more slowly, as the onset of the rainy season occurs earlier in the tropical Ucayali sub-basin and later in the equatorial Marañón sub-basin (Espinoza et al., 2009b). The huge size of the basin is the reason why the combinations of different hydro-climatic regimes produce such hybrid regimes (on this topic, see for instance Molinier et al., 1996; Ronchail et al., 2006; Ovando et al., 2016).

Centiles of the water level time series are used to define critical hydrological dates and periods during the annual hydrological cycle focusing on the flood recession period. The following are working definitions of the different parameters for the purpose of this study. The duration of the low-water (LW) period is defined as a portion of the year when the daily water level is below the lower tercile (C33; 4.5 m) of the 1985–2015 period (Fig. 1b). The beginning of the LW period is the first date with a water level below C33 (first C33) during at least 10 days, and the end of the LW period is the date following the first C33 with a water level above C33 during at least 10 days (second C33). The first C33 occurs July 20, on average, and the second C33 on November 11 (Table 1a).

The speed at which the water falls before the low-water period is estimated by computing the number of days between the first 66th centile (C66; 7.3 m) and the first C33. On average, the first C66 occurs on June 13 and the first C33 occurs 38 days later. The speed at which the water rises after the low-water period is estimated by computing the number of days between the second C33 and the first following C66. It is remarkable that the average of annual C66 dates (January 19, Table 1a) is not the same as the date of C66 computed on the mean 1985–2015 cycle (February 17, Fig. 1b). This is because the water rise is far from linear; after reaching C66, the water level may fall again for a while and then begin to rise again.

Finally, “repiquetes” (inversions in direction (sign) of water level change greater or equal to 1 cm in amplitude) are also considered during the flood recession cycle. They are considered when the stage returns to its former level after the inversion, from May to September.

2.3. Statistical methods

To identify temporal trends in time series, we use the parametric Pearson coefficient (r) and the rank-based non-parametric Spearman (Spearman, 1904) and Kendall tests (Kendall, 1975). Statistical breaks in the time series are evaluated using the Pettitt method (Pettitt, 1979), a non-parametric test based on changes in the average and the range of the series; the Lee and Heghinian Bayesian test (Lee and Heghinian, 1977), which uses the average as an indicator of change in the time series thanks to an a posteriori Student’s distribution; and the Hubert segmentation procedure (Hubert et al., 1989), which verifies whether differences in average and standard deviation among periods are significant.

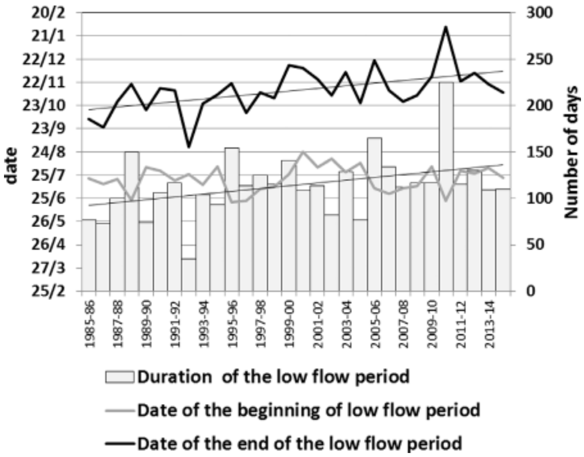

Fig. 2. Dates of beginning and end of low-stage period (gray and black lines) and duration of low-stage period (bars) during the hydrological cycle from May to April, at Tamshiyacu station, according to the 33rd (C33) centile values (4.5 m). Regression lines are shown for the duration and the ending date of the flood recession period.

Composite analysis is used to compare groups of years with hydrological parameter values lower than the first tercile to years with parameter values higher than the last tercile during the 1985–2009 period (the common period for rainfall and hydrological data). This enables us to compare water level, rainfall, dry-day frequency (DDF; days with rainfall < 1 mm/day), wet-day frequency (WDF; days with rainfall > 10 mm/day) during years with early and late beginning of the low-water period, early and late ending, long and short duration of the low-water period, and rapid and slow decrease and increase of the water level. The Student test allows comparison of the difference between the averages of two sub-samples.

3. Evolution of parameters of the flood recession period

3.1. The beginning of the low-water (LW) period

During the 1985–2015 period, the water level in the Amazon River reaches the 66th centile (C66; 7.3 m) on June 13, on average. This date changes over time, occurring as early as the beginning of May (in 1995) or later, at the end of July (1989), but there is no notable trend or break (Table 1a).

The mean date of the beginning of the LW period defined by the 33rd centile (C33; 4.5 m) is July 20 (Table 1a). It used to happen earlier (late June) in the middle of the 1990s, and later (in August) at the beginning of the 21st century. But no significant trend is observed in this time series (Fig. 2).

Fig. 3 shows the composites of water level and rainfall during years with early and late onset of the LW period. Years with an early onset are characterized by a lower than usual water level during the falling water period and the entire LW period until October (Fig. 3a). These years include those with the lowest rainfall described in the literature, i.e., 1995, 1998 and 2005 (Espinoza et al., 2011; Marengo et al., 2008, 2011; Zeng et al., 2008). In contrast, years with a late onset are characterized by water levels that are higher than usual during the falling water period, from June until the beginning of the LW period (Fig. 3a).

Rainfall is lower during years with an early onset of the LW period than during years with a late onset (Fig. 3c); the differences are significant at the 90% level from March to early May, and at the 95% level from the end of May until mid-June (+1.2 mm/day) and from the end of June until July 10 (+1.5 mm/day). This probably corresponds to rainfall over the northern part of upper Amazon basin (Marañón basin), where rainfall is more abundant during the autumn and austral winter, compared to the Ucayali basin (Espinoza et al., 2009a).

In accordance with these results, wet-day frequency (WDF) values are high (low) in June and July during years with a late (early) onset ($p < 0.1$) (Fig. 4a) and dry-day frequency (DDF) values are high (low) ($p < 0.1$) in May, July and September during years with an early (late) onset (Fig. 4c).

3.2. The end of the low-water (LW) period

The end of the LW period generally occurs at the beginning of November, with dates varying substantially, from the end of September, as in 1992, to the beginning of February year + 1, as in 2010 (Table 1a).

A composite of early ending episodes shows a higher than usual water level during the peak of the LW period and a sharp rise in October and November (Fig. 3b), while the composite of late ending episodes is characterized by very low water levels during the peak of the LW period (September) and water levels below average from October to late December.

The corresponding difference in rainfall between late and early endings is significant ($p < 0.1$) during a few days from mid- to late August (0.75 mm/day) (Fig. 3d). Comparing dry-day frequency (DDF) during late and early endings, it appears to be slightly

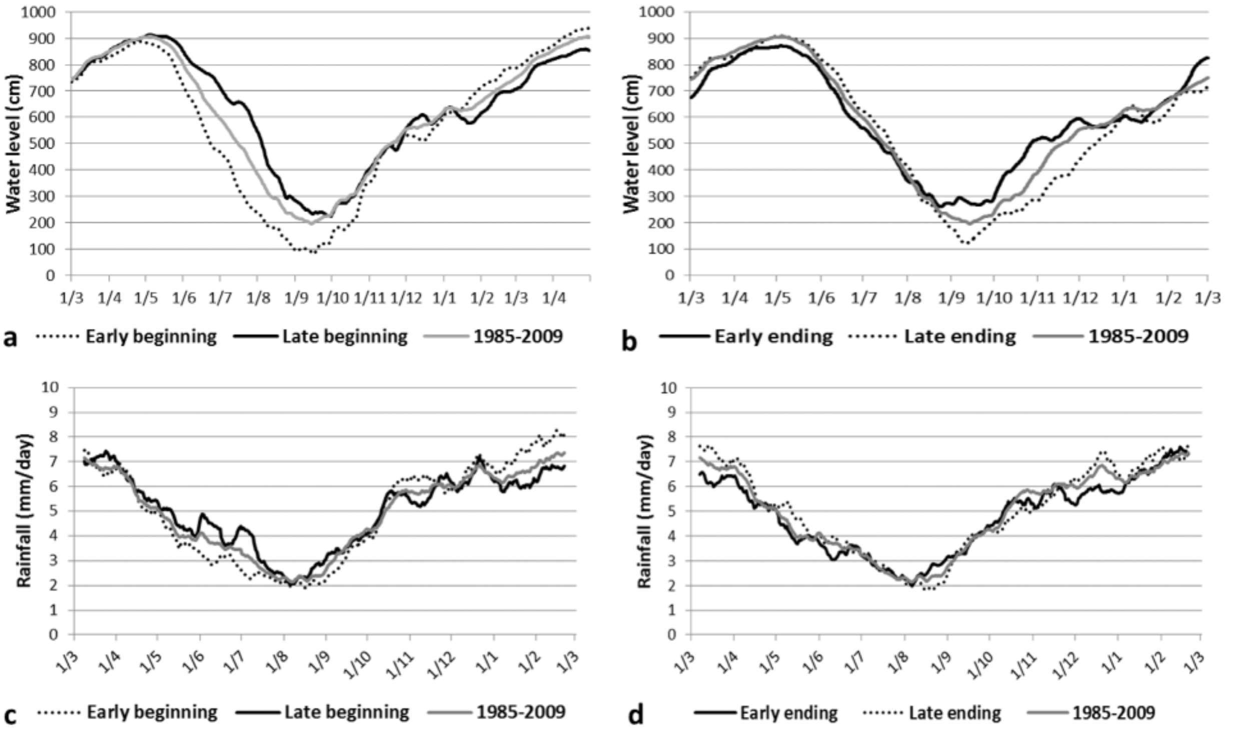

Fig. 3. Composite of Amazon River water level (cm) at Tamshiyacu station during years with an early or late a) beginning, b) ending of the low-water period. Composite of basin-averaged rainfall (mm/day) in the upper Amazon basin at Tamshiyacu during the same years with an early or late c) beginning, d) ending of the low-water period. Rainfall is smoothed using a 15-day moving average. Years with an "early beginning" represent 33% of the years with the earliest dates: 1988, 1995, 1996, 1997, 1998, 2005, 2006 and 2007. Years with a "late beginning" represent 33% of the years with the latest dates: 1989, 1990, 1994, 2000, 2001, 2002, 2004 and 2009. Years with an "early ending" represent 33% of the years with the earliest dates: 1985, 1986, 1987, 1989, 1992, 1996, 2004 and 2007. Years with a "late ending" represent 33% of the years with the latest dates: 1988, 1995, 1999, 2000, 2001, 2003, 2005 and 2009.

higher from July to October and significant ($p < 0.1$) in September (Fig. 4d) when the end of the LW period occurs later than usual. It is noteworthy that an early ending of the LW period is followed by a stop in water rising from November to January (Fig. 3b), and is accompanied by a consistent decrease in WDF (Fig. 4b). Conversely, after a late ending, the water level increases more abruptly (Fig. 3b), in association with heavy rains (Fig. 3d) and high WDF in December (Fig. 4b). Such an abrupt transition has been observed, for example, from the extreme September 2010 very low discharge (8300 $m^3 s^{-1}$) to one of the highest discharges in April 2011 (49 500 $m^3 s^{-1}$), recorded at Tamshiyacu (Espinoza et al., 2012b).

A significant positive trend in the date of the end of the LW period ($R^2 = 0.24$, $p < 0.01$) is detected (Table 1a and Fig. 2). A significant ($p < 0.10$) break point is also observed in 1998, with later dates afterward; the end of the LW period occurs at the end of October before 1998 and at the end of November afterward (Fig. 2). This result is consistent with other studies by the authors about trends and breaks in the water level during different periods of the year (not shown), which highlight the decrease in the September-October-November (SON) water level ($R^2 = 0.2$, $p < 0.02$) during the 1985–2015 period, with a break in 1994 detected by all the tests (not shown). There is also a significant relationship ($R^2 = 0.63$, $p < 0.001$) between the date of the end of the LW period and the SON water level. The positive trend of the date of the end of the LW period may be related to the positive trend in DDF in the southern Ucayali basin (Fig. 4e).

3.3. Duration of the low-water (LW) period

Fig. 5a compares years with short and a long LW duration. During years with long LW periods, water level is below average from June until the end of the year; the water level reaches values as low as one meter or less during the two first weeks of September. Short LW periods, in contrast, are characterized by above-average water levels, especially from mid-July until the end of the year. The LW period generally lasts 114 days between the first (July 20) and the second (November 11) C33, but it has been as short as 73 days in 1986, a year with significant inundations, and as long as 165 and 225 days during the 2005 and 2010 dry years, respectively (Table 1b and Fig. 2).

Fig. 2 shows that the duration of the LW period has regularly exceeded 100 days since 2005, and that it was nearly a month shorter at the beginning of the studied period. A significant trend ($R^2 = 0.15$, $p < 0.05$) is observed in this series, as well as a rupture in 1994, as indicated by the Pettit test: the duration of the LW period was 93 days before 1994, and it increased to 125 days afterward (Table 1b). Other studies by the authors about trends and breaks in the water level during different periods of the year (not shown) demonstrates that the date of the break in the duration of the LW period is the same as that observed in the SON water level

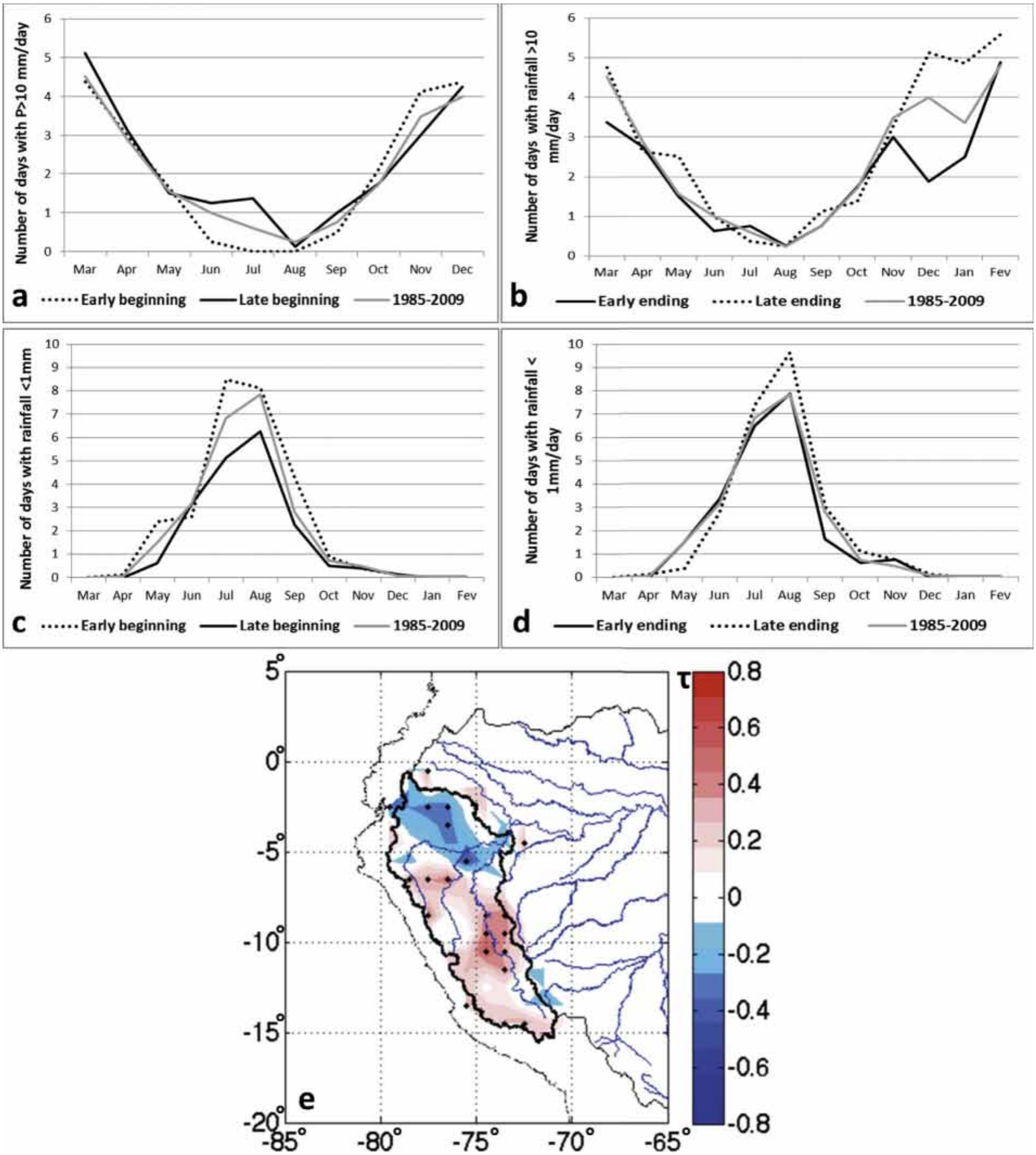

Fig. 4. Composite of monthly wet-day frequency (WDF, days with P > 10 mm) during years with an early or late a) beginning, b) ending of the low-water period, and composites of monthly dry-day frequency (DDF, days with rainfall < 1 mm) during years with an early or late c) beginning, d) ending of low-water period. Each case represents 33% of the years during the 1985–2009 period. Years with an early beginning are 1988, 1995, 1996, 1997, 1998, 2005, 2006 and 2007. Years with a late beginning are 1989, 1990, 1994, 2000, 2001, 2002, 2004 and 2009. Years with an early ending are 1985, 1986, 1987, 1989, 1992, 1996, 2004 and 2007. Years with a late ending are 1988, 1995, 1999, 2000, 2001, 2003, 2005 and 2009. e) Spatial distribution of Kendall coefficient values ($p < 0.05$ are indicated with dark dots) resulting from trend test on gridded April-August DDF values (1985–2009) in the Amazon basin at Tamshiyacu.

series. The two series are strongly correlated ($R^2 = 0.66$, $p < 0.001$). Again, these results are consistent with an upward trend in the frequency of dry days in the upper Amazon basin (Fig. 4e) and with a break in this time series in 1995 (Espinoza et al., 2016).

The duration of the LW period is strongly and positively correlated with the date of the end of the LW period ($R^2 = 0.66$, $p < 0.001$) and negatively correlated with the date of the beginning of the LW period ($R^2 = 0.30$; $p < 0.001$). Six out of eight years with a short duration are also years with an early ending, and five out of eight years with a long duration are also years with a late

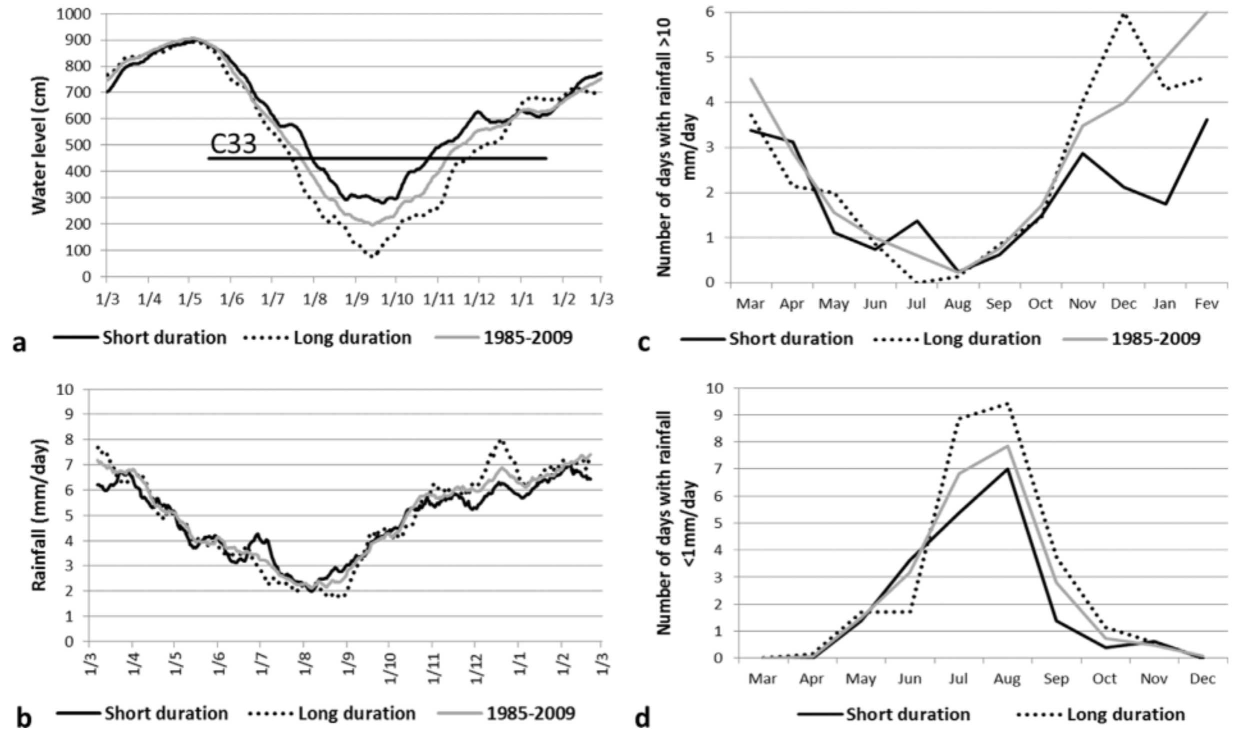

Fig. 5. Composite of a) the water level (cm) of the Amazonas River at the Tamshiyacu station, b) precipitation (mm) in the upper Amazon basin at Tamshiyacu, and c) wet-day frequency (WDF, $P > 10$ mm) and d) dry-day frequency (DDF, $P < 1$ mm) during years with short or long duration of the low-water period. Rainfall is smoothed using a 15-day moving average. Each case represents 33% of the years during the 1985–2009 period. Years with a short duration are 1985, 1986, 1987, 1989, 1992, 1994, 2002 and 2004. Years with a long duration are 1988, 1995, 1997, 1999, 2003, 2005 and 2006.

ending.

More rainfall than normal is registered when the duration of the LW period is shorter than usual (Fig. 5b), particularly during 10 days at the end of June-beginning of July (+1.3 mm/day, $p < 0.05$) and from mid-August to the first days of September (+1 mm/day, $p < 0,05$). Similarly, the number of wet days is significantly higher ($p < 0.1$) in July when the LW duration is shorter than usual (1.4 days instead of 0) (Fig. 5c). When the LW period is long, the number of dry days is generally higher from July to October and is significantly higher ($p < 0.05$) in July and September: 8.8 days instead of 5.4 in July and 3.7 instead of 1.4 in September (Fig. 5d).

It is noteworthy that after a long LW period, the water level increases regularly and rapidly (Fig. 5a) in association with an onset of the rainy season that occurs later and more vigorously than usual: rainfall (Fig. 5b) and the number of wet days (Fig. 5c) are higher than usual in November and December. The opposite is true when the LW period is shorter than usual: rainfall and wet days are less abundant and frequent from November to January and the water level remains around 600 cm until the end of January.

3.4. Speed of water falling and rising

The speed of the water falling and rising is measured by the numbers of days between the first 66th centile (C66–7.3 m) and the first C33 (4.5 m) for falling water, and between the second C33 and the second C66 for rising water.

The average duration of water falling, between the mean date of the first C66 (June 13) and the mean date of the first C33 (July 20) (Table 1a), is 38 days, and the mean speed of water falling is 7.4 cm/day. This value is similar to the speed estimated by Coomes et al. (2016) for the station at Iquitos during the 1968–2013 period. These values vary between 12 days (23 cm/day) in 1988 and 85 days (3.3 cm/day) in 2004 (Table 1c and Fig. 6a).

The speed of water rising is much lower, as noted by Hiraoka (1985): the average duration between the second C33 and the second C66 is 70 days (4 cm/day) and varies from 20 days (14 cm/day) in 1993–149 days (1.9 cm/day) in 1985 (Table 1c and Fig. 7a).

Unlike water falling, which shows considerable interannual variability but no trend (Fig. 6a), the speed of the water rising increases with time: that is, the number of days separating the second C33 and C66 decreases significantly during the 1985–2015 period ($R^2 = 0.22$, $p < 0.02$; Table 1c and Fig. 7a). During the first 10 years of the studied period, the water level rose from C33 to C66 in about three months (82 days) on average, and the interannual variability was very high (the coefficient of variation of the 1985–1996 period is 0.51). Since the late 1990s, the water level has increased from C33 to C66 in about 50 days, and even more rapidly since 2009, and the coefficient of variation for the 1997–2015 period decreased to 0.39.

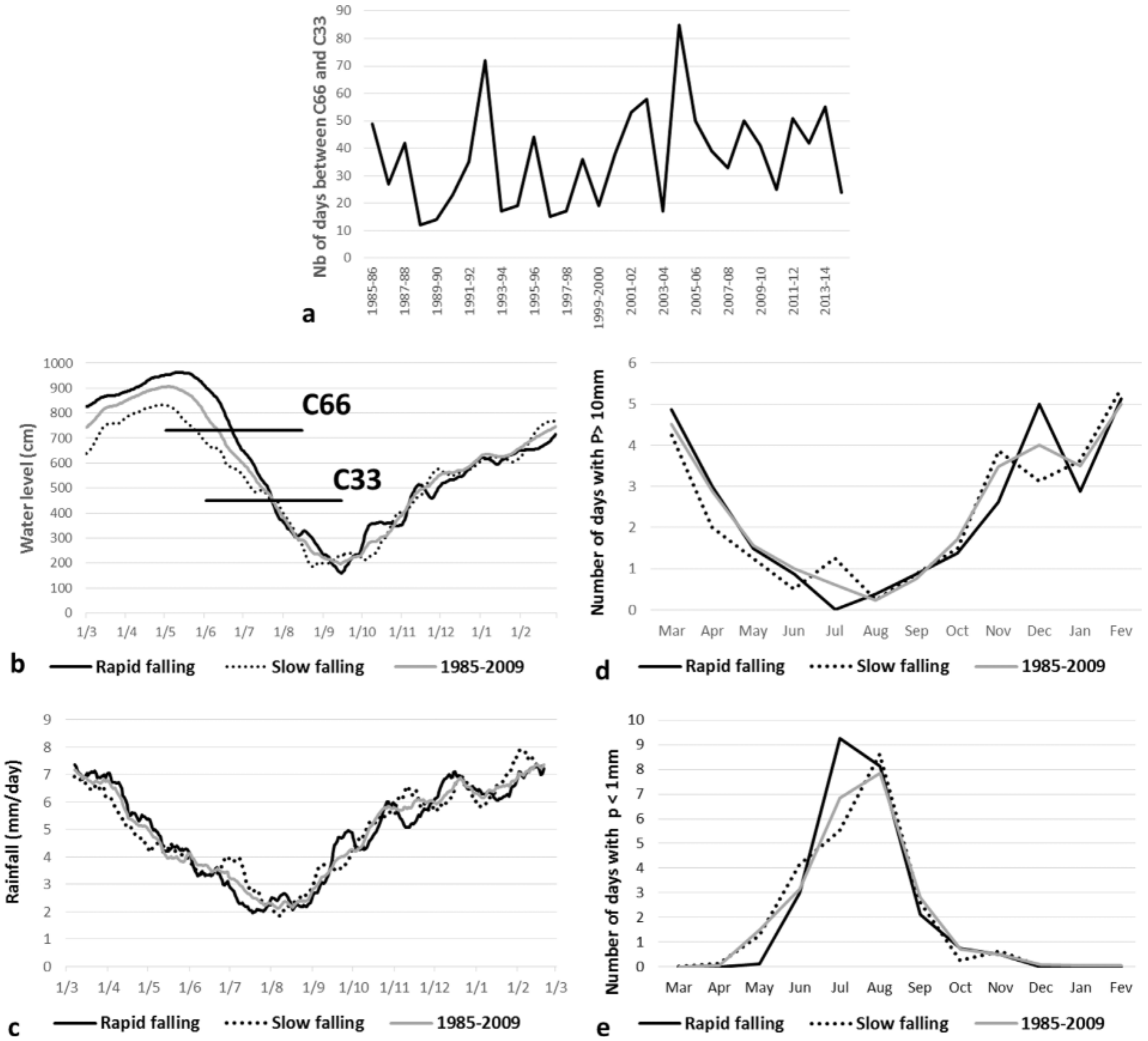

Fig. 6. a) Number of days between the first 66th centile of the water level in the Amazon River at Tamshiyacu and the first 33rd centile of the May-April hydrological cycle (1985–2015). Composite of b) water level (cm) of the Amazon River at the Tamshiyacu station and c) basin-averaged- precipitation (mm) in the upper Amazon basin at Tamshiyacu, d) wet-day frequency, e) dry-day frequency during years with a slow or rapid decrease of water level before the low-water period. Rainfall is smoothed using a 15-day moving average. Each case represents 33% of the years during the 1985–2009 period. Years with a rapid decrease are 1988, 1989, 1993, 1994, 1996, 1997, 1999 and 2003. Years with a slow decrease of water level are 1985, 1992, 1995, 2001, 2002, 2004, 2005 and 2008.

Figs. 6b and 7b show that years with a rapid (slow) water level decrease are characterized by a higher (lower) than usual water level during the former flood period. Years with a rapid (slow) increase are characterized by a high (very low) water level during the flood recession period. Moreover, rapid water increases are distinguished by a regular increase of the water level until the beginning of the next year, while slow increases are characterized by a break in the water rising from December to mid-January (Fig. 7b).

A rapid falling of the water level, compared to a slow falling, is related to higher-than-usual rainfall, significant especially in April ($-0,9$ mm/day, $p < 0.05$), and to rainfall lower than usual in part of July ($+0,8$ mm/day, $p < 0.05$) (Fig. 6c). Consistently, a rapid falling is related to a low number of wet days (Fig. 6d) and a high number of dry days (Fig. 6e) in July while the opposite is observed when the water level falls slowly.

A rapid increase of the water level after the recession period can be related to higher rainfall than when the increase is slow, at the beginning of June ($+0.7$ mm/day, $p < 0.1$), in August ($+0.7$ mm/day, $p < 0.05$) and also from mid-November until the end of December ($+1.2$ mm/day, $p < 0.1$) (Fig. 7c). Consistently, a rapid increase is also associated with a high number of wet days in June and August and in November and December ($p < 0.05$, Fig. 7d), i.e. during the LW period and at the beginning of the rainy season, and with fewer dry days in August and October ($p < 0.1$, Fig. 7e). Other studies by the authors about rainfall trends (not shown) highlight that a positive trend in November-December basin-averaged rainfall at Tamshiyacu ($R^2 = 0.21$, $p < 0.01$) may explain the trend in the velocity of the water rising during the study period (not shown).

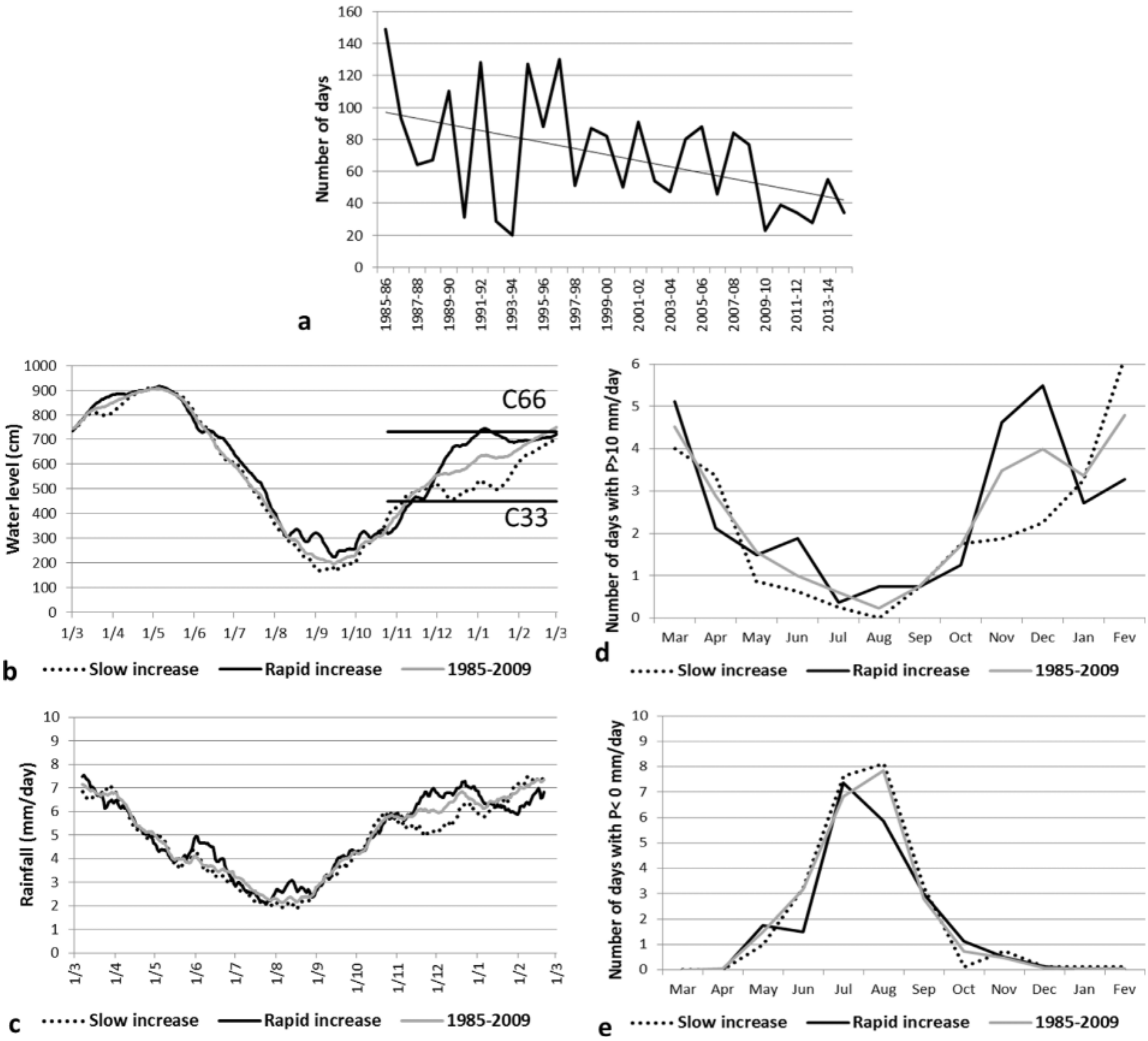

Fig. 7. a) Number of days between the second 33rd centile of water level in the Amazonas River at Tamshiyacu (after the low-water period) and the second 66th centile of the May-April hydrological cycle (1985–2015). Composite of b) water level (cm) of the Amazon River at the Tamshiyacu station, and of c) basin-averaged-precipitation (mm) in the upper Amazon basin at Tamshiyacu, d) wet-day frequency, e) dry-day frequency during years with a slow or a rapid increase in water level after the low-water period. Rainfall is smoothed using a 15-day moving average. Each case represents 33% of the years during the 1985–2009 period. Years with a rapid increase are 1990, 1992, 1993, 1997, 2000, 2003, 2006 and 2009. Years with a slow increase of the water level are 1985, 1989, 1991, 1994, 1996, 1998, 2001 and 2005.

The speed of water rising is not significantly related to the duration of the LW period.

3.5. Repiquetes

“Repiquetes,” which are inversions in direction (sign) of stage change greater or equal to 1 cm in amplitude, are analyzed during the recession period at the Tamshiyacu station. Fig. 8a shows the example of 2007–08, when 10 repiquetes higher than 1 cm and six higher than 20 cm are observed between mid-June and October, in association with heavy rainfall during the preceding days.

An analysis of the distribution of repiquetes from May to September shows that the most frequent are the weak ones, those that are lower than 10 cm (110 out of 235; Fig. 8b). However, 48 out of 235 events exceed a 50 cm rise, 18 a one-meter rise and three a two-meter rise. The highest (2.64 m) was observed in June 1990, and the two others in August 1997 (2.44 m) and July 2002 (2.27 m). The frequency of small repiquetes is in accordance with Coomes et al. (2016), but these authors found repiquetes exceeding five meters at the Iquitos station and for a different period (1968–2013).

Repiquetes lower than 20 cm are more frequent in May (one per year, on average) and then are equally distributed from May to September (Fig. 8c), while those higher than 20 cm are more frequent from the first fortnight of July until the first fortnight of

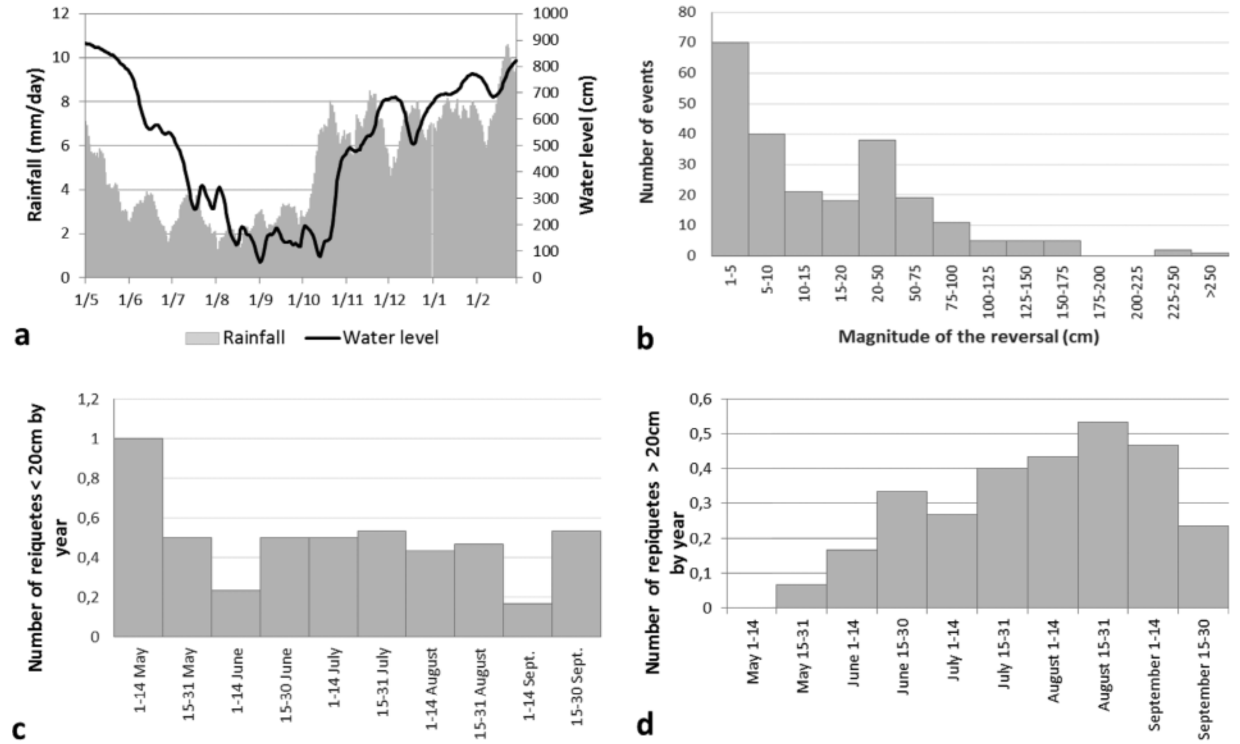

Fig. 8. a) Water level (cm, line) at Tamshiyacu station and rainfall (mm/day, bars) in the upper Amazon basin at Tamshiyacu during a flood recession cycle including repiquetes, or inversions in direction (sign) of stage change (2007–08), b) Number of repiquetes as a function of the magnitude of the reversal (1985–2014). Note that magnitude values are gathered in groups of different amplitudes. c) Average (1985–2014) annual number of repiquetes lower than 20 cm, by fortnight, from May to September. d) Average (1985–2014) annual number of repiquetes higher than 20 cm, by fortnight. Repiquetes are considered when the stage returns to its former level after the inversion.

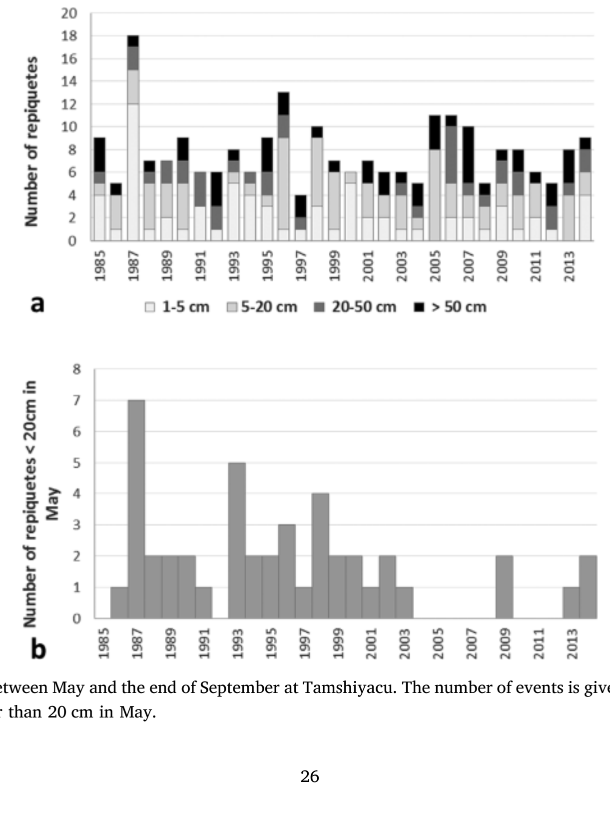

Fig. 9. a) Annual number of repiquetes between May and the end of September at Tamshiyacu. The number of events is given for four ranges of reversal magnitude. b) 1985–2014 evolution of repiquetes lower than 20 cm in May.

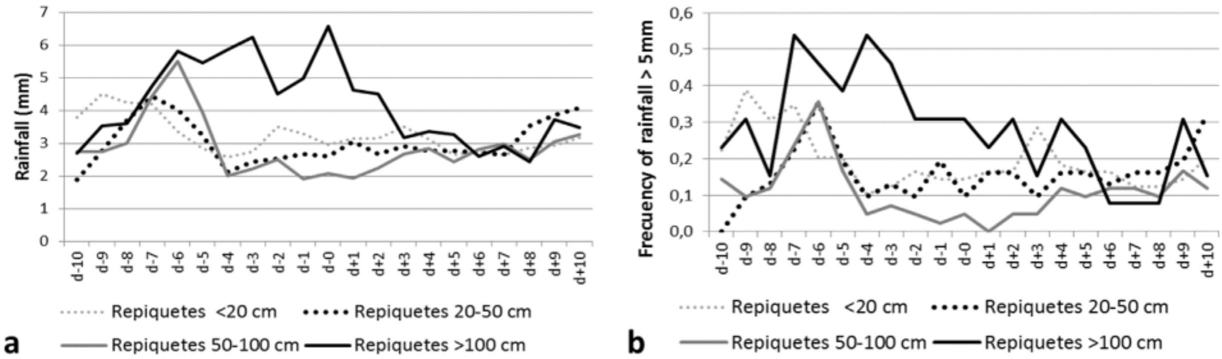

Fig. 10. a) Rainfall in the upper Amazon basin at Tamshiyacu (in mm/day) and b) frequency of rainfall exceeding 5 mm during the 10 days preceding (d − 10 to d − 1) and following (d + 1 to d + 10) the beginning of a repiquete event (d0) and for repiquetes during the 1985–2009 period with a water-level increase < 20 cm, between 20 and 50 cm, between 50 and 100 cm and greater than one meter. The selected events are those with no water rise during the 10 preceding days.

September (Fig. 8d). Generally, there is an average of 7.7 repiquetes by year (three if only those higher than 20 cm are considered), which is in accordance with Coomes et al. (2016), who found five to six events per year in Iquitos. The frequency of repiquetes shows an important interannual variability: 18 events were registered in 1987, but only four in 1997 as there can be none of them as in 2000 (Fig. 9a). Neither the annual number of repiquetes nor the number of repiquetes by elevation range shows any trend (Fig. 9a). Nevertheless, a sudden decrease in the number of weak repiquetes is observed in May since the beginning of the 21st century (Fig. 9b), which is not related to changes in rainfall.

While small repiquetes generally last less than a week, those higher than 20 cm last 14 days on average, from the beginning of the inversion until the stage returns to its former level. This result is similar to Coomes et al. (2016).

Basin-averaged daily rainfall up to Tamshiyacu has been analyzed during the 10 days before and after the beginning (d0) of a repiquete event, from d − 10 to d + 10. Rising of less than one meter is associated with prior rainfall generally exceeding 3 mm, the 15 May to 15 September average daily rainfall, during three to four days about one week before the beginning of the repiquete event (Fig. 10a). It is noteworthy that weak repiquetes, lower than 20 cm, are related to a rainfall peak on the ninth and eighth days before the beginning of the repiquete (d − 9 and d − 8), those between 20 and 50 cm to a peak d − 7 and those between 50 and 100 cm to a high peak d − 6. The rainfall peaks are lower (4.5 mm/day) for repiquetes lower than 50 cm and higher (> 5 mm/day) for repiquetes higher than 50 cm.

Rising of more than one meter is associated with daily rainfall exceeding 5 mm/day during nearly the entire week preceding the repiquete, and average accumulated excess rainfall during the entire period is 20 mm. During the very strong event in July 2002, rainfall excesses, when compared to average rainfall, reached 70 mm during the period between d − 7 and d + 2. Analyzing the intensity of rainfall, it appears that a week before a small repiquete, daily rainfall higher than 5 mm represents about 30% of daily values (Fig. 10b). The strongest repiquete events are more frequently related to intense rainfall: 40% of the d − 7 to d − 3 days show rainfall exceeding 5 mm/day.

In conclusion, strong events appear to be related to heavy and continuous rainfall during the week preceding the repiquete. Smaller repiquete events, in contrast, are related to a peak in rainfall about a week before the beginning of the event.

4. Synthesis and perspectives

This work contributes to the analysis of key hydrological parameters of the flood recession period (dates of beginning and end of the low-water period, duration of the low-water period, speed of water falling and rising, occurrence of repiquetes) in the upper Amazon basin at the Tamshiyacu station (Peru) and their evolution during the 1985–2015 period. The lower tercile of the daily water level (4.5 m) in the upper Amazon River at Tamshiyacu (Peru) during the 1985–2015 period is used to define the low-water (LW) period. This period begins, on average, at the end of July and ends in the first days of November, lasting about four months. The starting date of the LW period varies little during the study period and depends on the amount of rainfall observed from the end of May to the beginning of July. The ending date varies substantially over time, however, and occurs later now (end of November) than it used to (end of October), with a significant break in 1998. Consequently, the duration of the LW period, which varies considerably at an interannual time scale (from 2.5 to 7.5 months), also shows a positive trend, with a break in 1994; it lasted 93 days on average before 1994 and 125 days afterward. Both variables are highly correlated with the September-October-November (SON) water level, which decreases significantly during the study period and also shows a break in 1994. The trend in the date of the end of the LW period and in the duration of the low stage can be attributed to the increase in dry-day frequency reported in the central and southern parts of the upper Amazon basin (Espinoza et al., 2016). This is also consistent with the increasing length of the dry season documented in the southern Amazon (Li and Fu, 2006; Carvalho et al., 2011; Marengo et al., 2011; Dubreuil et al., 2012; Fu et al., 2013; Yin et al., 2014; Arias et al., 2015; Debortoli et al., 2015; Espinoza et al., 2016).

The duration of falling and rising water level is defined as the number of days between the first and the second terciles of water level before and after the LW season, respectively. While the water falling duration (38 days on average) did not change over time, the water rising duration at the end of the LW period decreased from three to two months during the study period. A rapidly falling water level is related to decreased rainfall in July and an increase in dry-day frequency. A rapid rising is related to abundant and intense rainfall in November-December, which also characterizes late endings and long durations of the LW period. The positive trend in rainfall in November-December may explain the increasing speed of the water rising.

The choice of thresholds for the flood recession period parameters (C33, C66) is actually a limitation of the study. It is unclear how the results of this study, particularly the observed trends, might depend on the chosen value. However, similar results are obtained when defining the LW period with C20, the 20th centile, instead of C33 (not shown).

“Repiquetes,” or inversions in the direction (sign) of stage changes exceeding 1 cm, are frequent: eight per year, on average, or three when considering those higher than 20 cm. During the 1985–2015 period, 18 events exceeded a one-meter rise, and three exceeded two meters. They are related to unusually high and intense rainfall peaks occurring six to nine days before the beginning of the repiquete, depending on its intensity. The strongest ones, which are more frequent between July and September, are associated with rainfall events exceeding 5 mm/day during nearly the entire week preceding the beginning of the repiquete. These events show no trend during the study period.

Our results show that the occurrence of extremes and changes in the parameters of the flood recession period is closely related to changes in rainfall during specific periods of the annual cycle. Rainfall itself is modulated by interannual and long-term variability in the sea surface temperatures (SST) of the Pacific and Atlantic oceans and in regional atmospheric circulation (Marengo, 2004; Marengo and Espinoza, 2015; Yoon and Zeng, 2010; Satyamurty et al., 2013; Espinoza et al., 2009a, 2013, 2016, among others). During the austral summer, for example, precipitation is related to the phases of the El Niño-Southern Oscillation events, with more rainfall during La Niña events, when the waters of the equatorial Pacific are colder than usual and when an abundant moisture transport flux is observed from the tropical North Atlantic and the Caribbean Sea toward the northwestern Amazon.

Dry events and high dry-day frequencies during the austral winter are related to warmer SST in the tropical North Atlantic and to weaker-than-usual trade winds and vapor transport toward the Amazon and enhanced subsidence over the Amazon basin. They may be amplified by El Niño events during the preceding summer (Zeng et al., 2008; Marengo et al., 2008, 2011; Espinoza et al., 2011, 2016). The current increase in dry-day frequency (and in the duration of the low-water period) may also be related to a warming trend in the tropical North Atlantic (Marengo et al., 2008, 2011; Yoon and Zeng, 2010; Fernandes et al., 2015; Espinoza et al., 2016) and to land use change in the Amazon basin (Wright et al., 2017).

Relationships between aspects of intra-seasonal variability of atmospheric circulation and the occurrence of repiquetes could be analyzed. Former works show that southern circulation patterns in South America associated with cold fronts are conducive to the development of convection and to rainfall in winter (Marengo et al., 1997; Garreaud and Wallace, 1998; Espinoza et al., 2012a). As a consequence, they may favor repiquetes.

The relationships between rainfall and ocean-atmosphere conditions and those between rainfall and flood recession parameters may indicate that these parameters could be predictable at intra-seasonal and interannual time scales. Further work could allow the development of an early-warning system to alert farmers of the characteristics of the forthcoming recessional period or the imminent occurrence of a repiquete.

Our results indicate that current hydrology patterns could be positive for recessional agriculture in Peru's Amazonian lowlands. The increased length of the low-water period and the decrease in the minimum water level could mean that more land may be available for agriculture during a longer time period, which would favor crop maturation. But repiquetes, one of the greatest risks to rice crops (List and Coomes, 2017), and more abrupt water rising, as documented in this study, could jeopardize crops of the recessional season. Decreased precipitation and an increase in dry day frequency could also affect agriculture in a region where there is no irrigation. Verifying the relationship between hydroclimatology and crop yields would imply 1) adapting the definition of parameters and the selected threshold to the crops of interest (vegetation zones related to fluvial dynamics imply that crops with shorter growing seasons are located near the water, while perennials and crops with longer growing seasons are cultivated on higher ground) (Denevan, 1984; Hiraoka, 1985); and 2) taking into account other variables, such as erosion (Mendoza et al., 2016), sediment quality, plant diseases, and pests such as birds and rats, which also affect crops (Rios Arevalo, 2005; List, 2016; List and Coomes, 2017). Such a study, which would require a large, multidisciplinary group of researchers, could provide information that would be useful for early warnings to farmers and agricultural insurance services (List, 2016; List and Coomes, 2017).

Conflicts of interest

None.

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