Impact of the Amazon tributaries on major floods at Óbidos

JOSYANE RONCHAIL[1], JEAN-LOUP GUYOT[2], JHAN CARLO ESPINOZA VILLAR[2], PASCAL FRAIZY[2], GÉRARD COCHONNEAU[3], EURIDES DE OLIVEIRA[4], NAZIANO FILIZOLA[4] & JUAN JULIO ORDENEZ[5]

1 *Université Paris 7- Denis Diderot and Laboratoire d'Océanographie et du Climat (LOCEAN-IPSL), case 100, 4 Place Jussieu, F-75005 Paris-France*
josyane.ronchail@lodyc.jussieu.fr

2 *Institut de Recherche pour le Développement and Universidad Agraria La Molina, casilla 18 1209, Lima 18, Peru*
3 *Maison de la Télédétection, 500 rue J.F. Breton, F-34093 Montpellier Cedex 05, France*
4 *Agência Nacional de Águas, Setor Policia, CEP 70610-200, Brasília, Brasil*
5 *Servício Nacional de Meteorología y Hidrología, Cahuide 785, Lima 11, Peru*

Abstract Major flooding of the Amazon river (with discharge over 250 000 $m^3 s^{-1}$) is analysed, using daily discharge at (a) Óbidos, the lowest gauged station on the Amazon River, 800 km from the ocean, (b) six gauge stations located on the main tributaries and characterized by different discharge regimes. During the 1984–2001 period major flooding on the main stream was related to the following features: (a) greater than usual high water in the Solimões River, the largest tributary, (b) delayed discharge peaks in the southwestern tributaries and the Amazonas River (Peru) and/or advanced discharge peaks on the Negro-Branco River, (c) unusual February–April discharge peaks in the western and northwestern tributaries, particularly in the Negro River. These two last features contribute to the simultaneous inflow of a great quantity of water from all the tributaries in April–May and may favour major flooding of the Amazon River at Óbidos.

Key words Amazon River; Óbidos; flooding; discharge; Brazil; Peru

INTRODUCTION

The Amazon basin at Óbidos is huge (4 677 000 km^2) and its main tributaries are located in various climatological regions: equatorial, and southern and northern tropics (Fig. 1 and Table 1). This is why different hydrological regimes are observed in the Amazon basin (Pardé, 1936; Molinier *et al.*, 1997). Consequently, flood time differs from one region to another and the peak discharge at Óbidos results from those in the different Amazon tributaries.

Callède *et al.* (2004) pointed out that higher than normal high water and mean discharge were observed around 1920, and 1950, and that they have become very frequent since the early 1970s. Nine events with runoff higher than 250 000 $m^3 s^{-1}$ occurred between 1970 and 2005, while four have been observed since the beginning of the century, in 1909, 1921, 1922 and 1953. Labat *et al.* (2005) also emphasize the Amazon long-term discharge variability using wavelet analysis.

In this paper, particular attention is given to recent major flooding in Óbidos and to the impact of the Amazon tributaries on these events. It is hypothesized that on the one hand, major flooding at Óbidos is associated with positive discharge anomalies in the tributaries. However, we wonder whether an anomalous high water level is observed in some tributaries only, or in all of them. On the other hand, major flooding at Óbidos may depend on the date of the flood in each basin. Is it related to delayed high water coming from the southern tributaries that experience their flood before Óbidos or, on the contrary, to sooner than usual floods in the northern tributaries that experience their peak after Óbidos? Is major flooding in Óbidos due to an anomalous concordance of flooding in the Amazon tributaries?

DATA

This study was realized using daily discharge data for 1984–2001 (Table 1). Water level series were recorded by ANA (Agência Nacional de Águas, Brasília, Brazil, http://www.ana.gov.br/) and SENAMHI (Servicio Nacional de Meteorología y Hydrología, Lima, Peru, http://www.senamhi.gob.pe/). Discharge values are computed within the Hybam project (Hydrogeodynamics of the Amazon basin, http://www.mpl.ird.fr/hybam/). Three virtual stations were created (Fig. 1):

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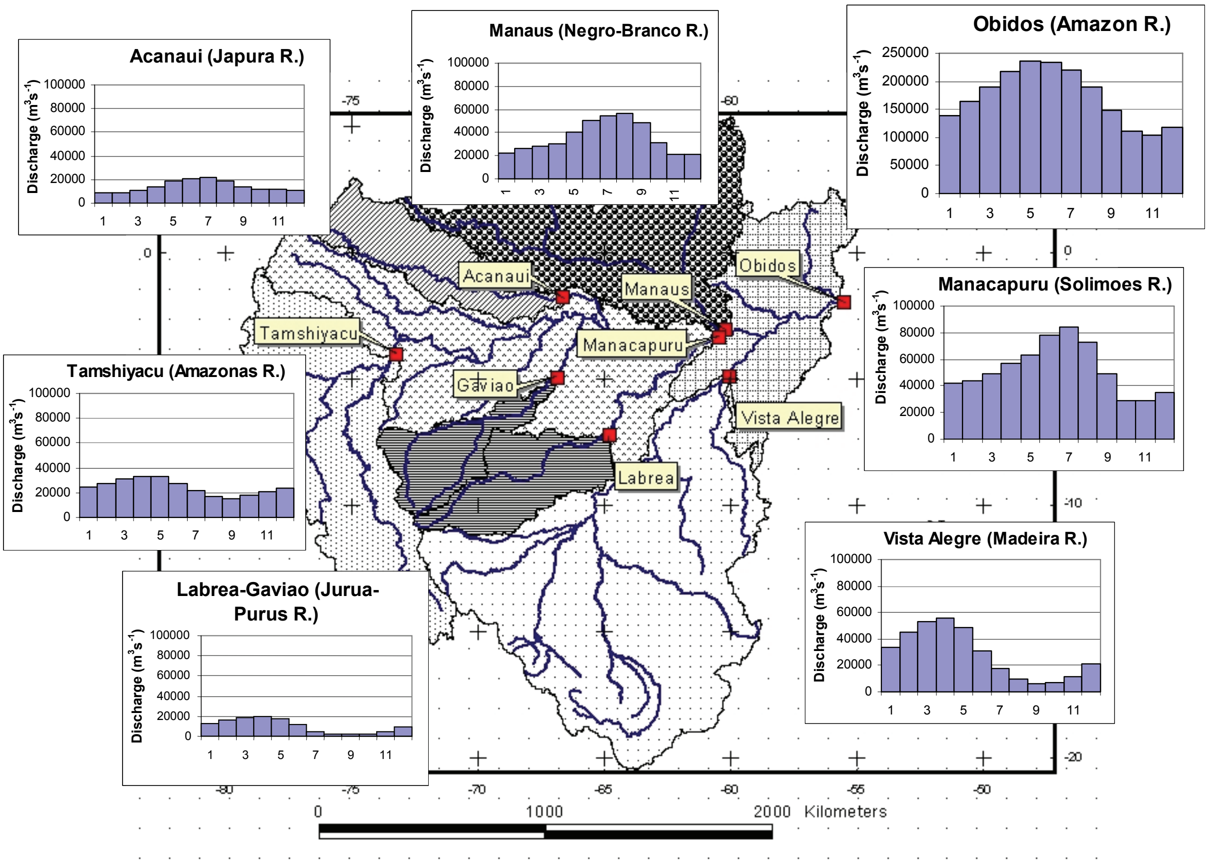

Fig. 1 Location and hydrological regimes of the Amazon River and its tributaries.

Table 1 Main characteristics of the gauging stations. Gavião-Labrea (GL), Solimões-Manacapuru (SM) and Manaus are virtual stations (see text).

	Latitude (°)	Longitude (°)	Surface (km²)	River	Period	Source
Vista Alegre	0.5 S	64.8 W	1 324 000	Madeira	67 / 02	ANA/HYBAM
GL			382 000	Purus-Jurua	72 / 01	ANA/HYBAM
Tamshiyacu	4 S	73.2 W	726 000	Amazonas	83 / 05	SENAMHI/HYBAM
Acanui	1.8 S	66.6 W	242 000	Japura	73 / 01	ANA/HYBAM
SM	3.3 S	62.8 W	797 000	Solimões	83 / 01	ANA/HYBAM
Manaus	3.1 S	60 W	697 000	NegroBranco	77 / 03	ANA/HYBAM
Óbidos	1.95 S	55.5 W	4 677 000	Amazon	68 / 05	ANA/HYBAM

(a) "Gavião-Labrea" values are the sum of the discharge of the Jurua River at Gavião and the Purus River at Labrea.

(b) "Solimões-Manacapuru" values are the difference between the Solimões River discharge at Manacapuru and the sum of its mains tributaries discharge: Amazonas at Tamshiyacu (Espinoza *et al.*, 2006), Japura at Acanui and Jurua-Purus at "Gavião-Labrea". This station represents the main stream of the Solimões River.

(c) "Manaus" values are the sum of the Amazon River discharge at Jatuarana (3.1°S and 59.7°W) and Careiro (3.2°S and 59.8°W), located downstream of the Negro and Solimões rivers confluence, minus the Solimões River discharge at Manacapuru.

The computational package Hydraccess (Vauchel, 2005) was used for data processing.

MAIN CHARACTERISTICS OF FLOODS ON THE AMAZON RIVER AND ITS TRIBUTARIES

The average 1984–2001 Amazon flood discharge at Óbidos is 238 000 $m^3 s^{-1}$ (Table 2) with extreme values varying from 274 400 $m^3 s^{-1}$ in 1989 to 194 600 $m^3 s^{-1}$ in 1992. The average flood

Table 2 Main characteristics of flooding at Óbidos and in the Amazon tributaries (1984–2001). Gavião-Labrea (GL), Solimões-Manacapuru (SM) and Manaus are virtual stations (see text).

	Qm ($m^3 s^{-1}$)	*Qf* ($m^3 s^{-1}$)	*Qfmax* ($m^3 s^{-1}$)	*Qmin* ($m^3 s^{-1}$)	*Df*	*Dfs*	*Dfl*
Vista Alegre	28 000	57 200	71 460 (1997)	50 470 (1987)	14/4	13/3	14/5
GL	10 000	20 000	23 400 (1997)	18 340 (1985)	12/4	10/3	19/5
Tamshiyacu	24 300	34 000	40 720 (1984)	29 460 (1995)	01/5*	22/3	21/5
Acanui	14 200	21 700	27 800 (1989)	18 460 (1992)	30/6	14/5	4/8
SM	53 000	85 000	108 810 (2000)	65 660 (1985)	13/7	6/6	10/8
Manaus	36 000	57 600	75 000 (1990)	48 000 (1992)	2/8	12/6	17/9
Óbidos	173 000	238 000	274 400 (1989)	194 600 (1992)	27/5	1/7	10/5

*A first flooding, equivalent to the May flooding, is sometimes recorded in January or February.

Qm: mean annual discharge; *Qf*: Mean annual flood; *Qfmax*: Maximum flood; *Qmin*: Minimum flood; *Df*: Mean date of the flood; *Dfs*: Date of the soonest flood; *Dfl*: Date of the latest flood.

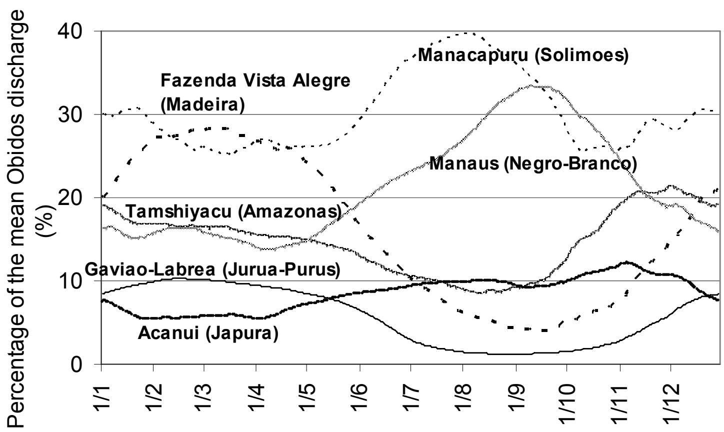

Fig. 2 Daily contribution (%) of the tributaries to the Amazon River discharge at Óbidos.

date is 27 May. However, during 1984–2001, floods occurred as early as 10 May 1992 and as late as 1 July 1994. Low water at Óbidos is observed in November and it represents half the flood value (Fig. 1). The contribution of the different tributaries to the Amazon River runoff varies with time in accordance with their annual cycle (Fig. 2).

The floods on the southwestern Amazon basins (Madeira and Jurua-Purus) occur first, around mid-April (Table 2). The hydrological regime is tropical with high water from March to May and low water in September. The seasons contrast strongly as low water is only a tenth of high water (Fig. 1). As the Madeira watershed is very large (Table 1), its mean discharge accounts for 16% of the Amazon River discharge (Table 2).

The Amazonas River at Tamshiyacu (Peru) drains most of the tropical Peruvian Amazon basin and some equatorial basins (Pastaza, Tigre and Santiago). This is why high water occurs later, 1 May, and discharge seasonality is weak (Table 2). Amazonas discharge at Tamshiyacu represents 14% of the mean Amazon discharge.

Western rivers (Japura, Negro-Branco and Solimões) drain very rainy regions. This explains why the Solimões and the Negro-Branco basins, although half the size of the Madeira basin, account for 30% and 20% respectively of the Amazon River discharge. Runoff seasonality is weak in these near-equatorial basins, with a maximum in July and a minimum in January.

The mean date for high water on the Amazon River at Óbidos is observed on 27 May, after the flood of the Madeira, Purus-Jurua and Amazonas rivers, but before the peaks of the Japura, Solimões and Negro-Branco rivers (Table 2).

THE GENESIS OF SIX MAJOR FLOOD IN ÓBIDOS (1984–2001)

Big floods are characterized by a discharge exceeding 250 000 $m^3 s^{-1}$ (Table 3(a)). During the three greatest floods, in 1989, 1997 and 1999, huge daily discharge values (over 260 000 $m^3 s^{-1}$) were recorded as well as long lasting strong values (2–3 months with over 250 000 $m^3 s^{-1}$ runoff).

Table 3(a) Main characteristics of major floods at Óbidos (1984–2001); Gavião-Labrea (GL), Solimões-Manacapuru (SM) and Manaus are virtual stations (see text).

OBIDOS:	1989	1994	1996	1997	1999	2000
Flood value ($m^3 s^{-1}$)	274 400	259 300	251 200	265 800	268 200	256 200
Date of flood	9/6	1/6	16/5	13/5	2/6	5/6
Days >250 000 $m^3 s^{-1}$	107	69	9	54	67	29
Date beginning > 250 000 $m^3 s^{-1}$	13/4	30/4	15/5	27/4	12/5	18/5
Date end > 250 000 $m^3 s^{-1}$	28/7	7/7	22/05*	19/6	16/7	15/6

* and from the 6/6 to the 10/6

Days >250 000 $m^3 s^{-1}$: number of days with a discharge over 250 000 $m^3 s^{-1}$; Beginning > 250 000 $m^3 s^{-1}$: date of the beginning of discharge over 250 000 $m^3 s^{-1}$; End > 250 000 $m^3 s^{-1}$: date of the end of discharge over 250 000 $m^3 s^{-1}$.

Table 3(b) Flood anomalies (percentage of the 1984–2001 flood average) in the main tributaries.

Percentage of the mean value	1989	1994	1996	1997	1999	2000
Vista Alegre	14	5	-4	25	-3	-7
GL	4	4	7	18	4	-5
Tamshiyacu	4	12	-4	2	14	6
Acanui	28		0	0	17	4
SM	17	23	13	22	28	3
Manaus	7	-5	22	-5	21	5

Table 4 Dates of flooding in the Amazon River tributaries during six major floods and during the 1984–2001 period. Delayed values in the Madeira (Vista Alegre), Jurua-Purus (Gavião-Labrea GL) and Amazonas (Tamshiyacu) rivers and advanced values in the Japura (Acanui), Solimões (Solimões-Manacapuru SM) and Negro (Manaus) rivers are shown in bold when there is a 10-day difference with the average 1984–2001 station value.

	1989	1994	1996	1997	1999	2000	Mean 1984–2001
Vista Alegre	27/3	13/3	**30/4**	9/4	11/4	5/4	14/4
GL	**22/4**	10/3	**13/5**	13/4	21/3	13/4	12/4
Tamshiyacu	9/5	**13/5**	22/4	23/4	**21/5**	**15/5**	1/5
Óbidos	9/6	1/6	16/5	13/5	2/6	5/6	27/5
Acanui	7/7		12/7	27/6	3/7	6/7	30/6
SM	8/8	8/8	14/7	23/7	3/8	10/8	13/7
Manaus	**7/7**	**14/6**	19/8	**12/6**	17/9	**1/7**	2/8

In 1989, strong positive maximum discharge anomalies were registered in the western basins (Solimões and Japura) and in the Madeira river (Table 3(b)). Moreover, the delayed peak of the Jurua-Purus and Amazonas rivers and the advanced flood of the Negro-Branco river (6 July instead of 2 August) led to concomitant high discharge in the different tributaries, during the rising stage on the Amazon River (Table 4). This phenomenon was reinforced by unusually high discharge values in December 1988 and in March–April 1989 in the Negro-Branco and Solimões rivers. The early flood of the Negro-Branco River and the late flood of the Solimões River contributed to the duration of the Amazon river flood (more than 3 months).

The 1994 flood is associated with higher than normal outflow along the Solimões-Tamshiyacu axis, i.e. in rivers flowing from Peru and Ecuador (Table 3(b)). Moreover, two features contributed to a big flood at Óbidos (a) higher than normal discharge values in the Solimões and Negro-Branco rivers from December 1993 to April–May 1994, (b) an advanced peak in the Negro-Branco River (14 June instead of 2 August) (Table 4).

The 1996 flood may be associated with higher than normal maximum discharge in the Solimões and Negro-Branco rivers and with delayed peaks in the southern rivers (Madeira and Jurua-Purus) (Tables 3(b) and 4). Moreover, an unusual discharge peak is notable in March–April in the Negro-Branco and the Japura rivers. This unusual peak, occurring during the southern tributaries' rising stage, may explain a strong and earlier than usual flood in Óbidos (16 May instead of 27 May).

In 1997, unusually high water was observed in southern tributaries, the Madeira and Jurua-Purus rivers, and along the Solimões river (Table 3(b)). Moreover, a February–March peak in the Negro-Branco and Japura rivers, and an earlier than usual flood in Manaus (12 June instead of 2 August) may also have contributed to a big and early flood at Óbidos (Table 4).

In 1999, the maximum discharge was greater than usual in all the tributaries except in the southern ones (Table 3(b)). Flooding was delayed in the River Amazonas (Table 4). Moreover, unusual peaks were observed in the Negro-Branco and Japura rivers in February–March and in the Solimões River in April; they coincide with the rising stage and flood in the southern affluent. On the other hand, a delayed flood in the Solimões and Negro-Branco rivers may have caused a long lasting flood at Óbidos (67 days).

Lastly, in 2000, weak positive maximum discharge anomalies were observed in the western tributaries (Table 3(b)). Moreover, a one-month early Negro-Branco River flood and a delayed flood on the Amazonas River are factors that explain the concomitant high discharge in the southwestern and northwestern affluent (Table 4).

CONCLUSION

The main characteristics of six major Amazon floods in Óbidos, during 1984–2001, are analysed using the daily discharge values of six Amazon tributaries.

In 1989, the biggest flood of the twentieth century was related to positive discharge anomalies across the whole basin. In the other cases, unusually high water is observed in groups of tributaries that are always different. Obviously, as it is the biggest tributary, a positive high water anomaly is generally observed in the Solimões River. The correlation between high water discharge in the Amazon River and in the tributaries is high with the Solimões (r = 0.77), weak with the Jurua-Purus, the Amazonas (Peru) and the Japura and non-significant with the Negro-Branco and the Madeira.

Major flooding at Óbidos is also related to out-of-phase flooding in the tributaries and to concomitant high discharge values in the different rivers. Delayed flooding was observed three times in the Amazonas River, twice in the Jurua-Purus River and once in the Madeira River. Advanced high water occurred four times in the Negro-Branco River. In 2000, as no strong high water anomaly was observed in the main tributaries, the Amazon flood may be directly associated with a delayed peak in the Amazonas River and an advanced one in the Negro-Branco River.

Major flood events are also related to the occurrence of out of phase and secondary peak discharges in the Negro-Branco River (1989, 1994, 1996, 1997, 1999), in the Japura River (1996, 1997, 1999) or in the main stream of the Solimões River (1989, 1994, 1999). In the Negro-Branco River, these discharge anomalies generally occur from February to April, are particularly strong (+20% during the three months) and are associated with an earlier than usual flood in Manaus (Fig. 3). The relationship between high water discharge at Óbidos and February–March–April discharge at Manaus is significant (r = 0.74). In the Japura and Solimões rivers, they are less frequent and the average discharge anomalies are weaker (+10%). The February–March–April discharge anomalies are in phase with the southern tributaries' rising stage and high water and contribute to major floods at Óbidos. The origin of these out-of-phase peaks in the western rivers deserves further investigations.

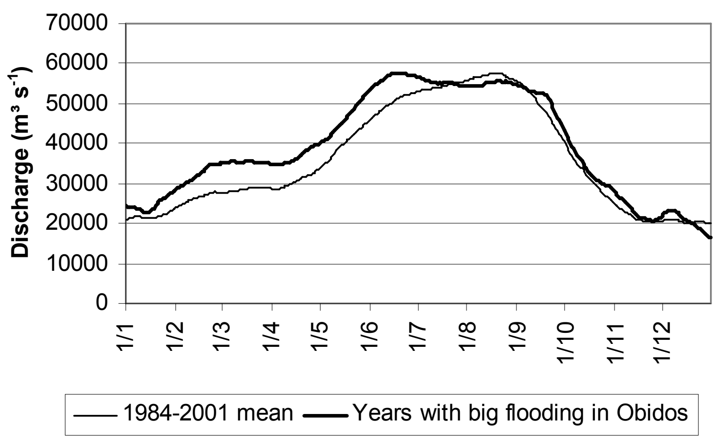

Fig. 3 Mean discharge of the Negro-Branco River during the 1984–2001 period (thin line) and during years with major flooding at Óbidos (1989, 1994, 1996, 1997, 1999 and 2000) (bold line).

In conclusion, each big flood at Óbidos seems to be a special event with its own causes. Nevertheless major floods have some features in common, such as a February–March–April unusual peak in the Negro-Branco River, a delayed flood in the southern basins and in the Amazonas River, and a high water level on the Solimões River, the greatest Amazon tributary. These variables should be accurately monitored in order to predict major floods at Óbidos.

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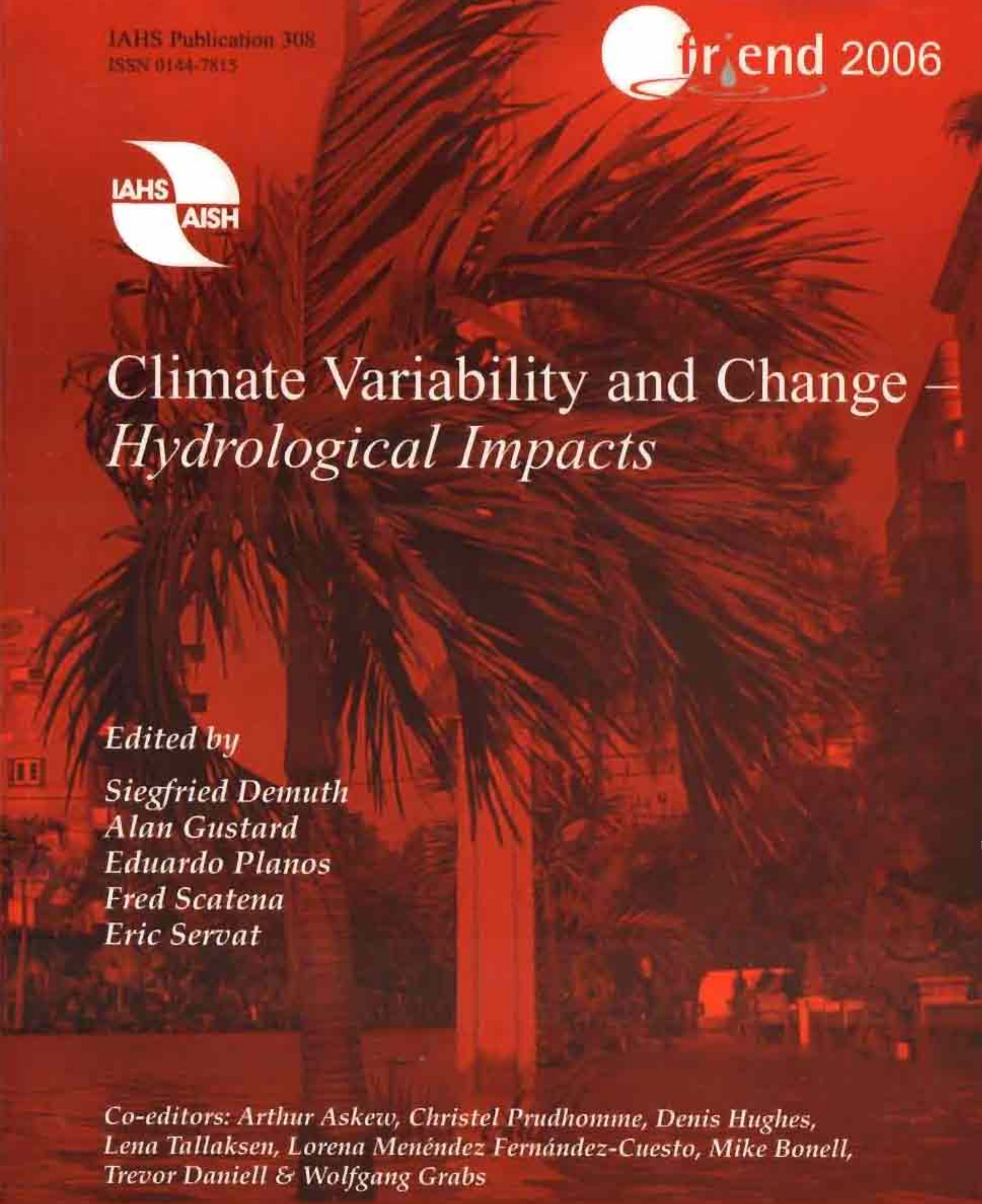

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