Hydrological Sciences Journal

ISSN: 0262-6667 (Print) 2150-3435 (Online) Journal homepage: https://www.tandfonline.com/loi/thsj20

Basin-scale analysis of rainfall and runoff in Peru (1969–2004): Pacific, Titicaca and Amazonas drainages

Waldo Sven Lavado Casimiro , Josyane Ronchail , David Labat , Jhan Carlo Espinoza & Jean Loup Guyot

To cite this article: Waldo Sven Lavado Casimiro , Josyane Ronchail , David Labat , Jhan Carlo Espinoza & Jean Loup Guyot (2012) Basin-scale analysis of rainfall and runoff in Peru (1969–2004): Pacific, Titicaca and Amazonas drainages, Hydrological Sciences Journal, 57:4, 625-642, DOI: 10.1080/02626667.2012.672985

To link to this article: https://doi.org/10.1080/02626667.2012.672985

Published online: 03 Apr 2012.

Basin-scale analysis of rainfall and runoff in Peru (1969–2004): Pacific, Titicaca and Amazonas drainages

Waldo Sven Lavado Casimiro[1,2,3], Josyane Ronchail[4], David Labat[2], Jhan Carlo Espinoza[5] and Jean Loup Guyot[2,4]

[1]*Servicio Nacional de Meteorología e Hidrología, SENAMHI, Casilla 11 1308, Lima 11, Peru*
wlavado@senamhi.gob.pe

[2]*Geosciences Environnement Toulouse (CNRS, IRD, Université de Toulouse, OMP), 14 Avenida Edouard Belin, F-31400 Toulouse, France*

[3]*Universidad Agraria La Molina (UNALM). Av. Universidad s/n La Molina, Lima 12, Perú*

[4]*Université Paris Denis Diderot, Sorbonne Paris Cité, F-75013 Paris, France*

[5]*Instituto Geofísico del Perú (IGP), Calle Badajoz 169, Mayorazgo IV Etapa, Lima 03, Peru*

Received 12 July 2010; accepted 25 August 2011; open for discussion until 1 November 2012

Editor Z.W. Kundzewicz; **Associate editor** Š. Blažková

Citation Lavado C., W.S., Ronchail, J., Labat, D., Espinoza, J.C. and Guyot, J.L., 2012. Basin-scale analysis of rainfall and runoff in Peru (1969–2004): Pacific, Titicaca and Amazonas watersheds. *Hydrological Sciences Journal*, 57 (4), 625–642.

Abstract According to the Peruvian agricultural ministry, the Pacific watersheds where the great cities and intense farming are located only benefit from 1% of the available freshwater in Peru. Hence a thorough knowledge of the hydrology of this region is of particular importance. In the paper, analysis of this region and of the two other main Peruvian drainages, the Titicaca and Amazonas are reported. Rainfall and runoff data collected by the Peruvian National Service of Meteorology and Hydrology (SENAMHI) and controlled under the Hydrogeodynamics of the Amazon Basin (HyBAm) project is the basis of this basin-scale study that covers the 1969–2004 period. Beyond the strong contrasting rainfall conditions that differentiate the dry coastal basins and the wet eastern lowlands, details are given about *in situ* runoff and per basin rainfall distribution in these regions, and about their different altitude–rainfall relationships. Rainfall and runoff variability is strong in the coastal basins at seasonal and inter-annual time scales, and related to extreme El Niño events in the Pacific Ocean. However, rainfall and runoff are more regular in the Andes and Amazonas at the inter-annual time scale. Warm sea-surface temperatures in the northern tropical Atlantic tend to produce drought in the southern Andes basins. Moreover, significant trends and change-points are observed in the runoff data of Amazonas basins where rainfall and runoff decrease, especially after the mid-1980s and during the low-stage season. Almost all the coastal basins show some change in minimum runoff during the last 35 years while no change is observed in rainfall. This means that human activity may have changed runoff in this region of Peru, but this hypothesis deserves more study.

Key words rainfall; runoff; Titicaca basin; Amazon; Pacific coast; Peru; tropical Atlantic

Analyse de la pluie et de l'écoulement au Pérou (1969–2004) : bassins versants du Pacifique, du Lac Titicaca et de l'Amazone

Résumé D'après le Ministère péruvien de l'agriculture, les bassins du versant Pacifique, qui concentrent les grandes villes et où se pratique une agriculture intensive, ne bénéficient que de 1% de l'eau douce disponible au Pérou. C'est pourquoi cet article présente l'hydrologie de cette région, dont la connaissance approfondie est d'une importance capitale pour l'économie du Pérou. Les deux autres grands bassins versants péruviens, celui, endoréique, du Titicaca et celui de l'Amazone, seront également étudiés. Les données mensuelles de précipitations et de débits pour la période de 1969–2004 à l'échelle du bassin versant, sont mises à disposition par le Service national de météorologie et d'hydrologie (SENAMHI) de Pérou, et elles sont analysées dans le cadre du programme « Hydrogéodynamique du bassin amazonien » (HyBAm). Au-delà du contraste classique entre bassins versants côtiers secs et plaines orientales humides, la répartition spatiale de l'écoulement et des pluies est détaillée avec, notamment, une régionalisation des liens entre pluie et altitude. Une variabilité temporelle élevée des précipitations et de l'écoulement est mise en évidence dans les bassins côtiers,

ISSN 0262-6667 print/ISSN 2150-3435 online

http://dx.doi.org/10.1080/02626667.2012.672985
http://www.tandfonline.com

à des échelles de temps saisonnière et interannuelle, en relation avec les événements extrêmes El Niño dans l'Océan Pacifique. Par contre, les précipitations et l'écoulement apparaissent comme moins variables dans les Andes orientales et en Amazonie au pas de temps interannuel. Cependant, des températures de surface de l'océan élevées dans le nord de l'Atlantique tropical ont tendance à produire des sécheresses dans les bassins andins méridionaux. Par ailleurs, des tendances et des ruptures significatives dans la moyenne sont observées en Amazonie où pluie et écoulement diminuent, surtout depuis le milieu des années 1980, durant la saison d'étiage. Dans presque tous les bassins côtiers, l'écoulement d'étiage est sujet à des tendances diverses (à la hausse ou à la baisse), au cours des 35 dernières années bien que de telles tendances ne soient pas visibles sur les séries de précipitations. Cela signifie que l'activité humaine peut être responsable de cette évolution sur la côte péruvienne. La confirmation de cette hypothèse nécessite des études complémentaires.

Mots clefs pluie; écoulement; bassin du Lac Titicaca; Amazonie; côte Pacifique; Pérou; Atlantique tropical

INTRODUCTION

The north–south Andes cordillera divides Peru (1 285 216 km^2) into three main drainages (Fig. 1), one draining towards the Pacific Ocean (Pacific drainage—Pd), another towards the Amazon basin (Amazonas drainage—Ad) and the southern, endorheic Lake Titicaca basin on the Altiplano (Titicaca drainage—Td). The Peruvian National Water Agency reports that the Pacific, Titicaca and Amazon drainages represent, respectively, 21.7%, 3.8% and 74.5% of the Peruvian territory and include 62, 13 and 84 main sub-basins, respectively (Ruiz *et al*. 2008). The multi-annual water balance (difference between rainfall and evapotranspiration) computed for the period 1969–1999 by UNESCO (2006) indicates that the available surface water is 16.4 mm year^{-1} in Pd, 129.8 mm in Td and 2696.6 mm in Ad. Unfortunately, the accessibility of freshwater resources in Peru is the converse of population density; 88% of the population lives along the Pacific coast, around Lake Titicaca and in the Andean zones of the Amazon basin, where only 2% of the Peruvian freshwater resources are available. Moreover, the greatest Peruvian cities (i.e. Lima, Arequipa and Piura) are in Pd with only 0.6% of the available freshwater in Peru. According to the agricultural ministry (http://www.minag.gob.pe), agriculture along the Pacific coast has been developed thanks to irrigation that uses about 80% of the available water, while domestic usage consumes about 12%. Private and public investments have been used in order to develop this infrastructure aimed at increasing agricultural exports. Water resources are also essential in the other drainages. For instance, a large rural population lives around Lake Titicaca and depends on water for farming produce. Moreover, transport activities in the Amazon basin are extremely dependent on rivers, due to the absence of roads in the dense forest, and transport services are interrupted as a result of extreme low water levels.

Most studies of Peruvian hydrology have focused on only one of the main drainages and seldom on all three of them. The aim of this study is to propose a synoptic outline of the mean characteristics of rainfall and discharge in Peru and of their recent variability, using a comprehensive set of rainfall and runoff data that covers the whole Peruvian territory (Pacific, Amazonas and Titicaca drainages). This is made possible thanks to the collection and the validation of information by the Peruvian National Meteorology and Hydrology Service (*Servicio Nacional de Meteorología e Hidrología*, SENAMHI, http://www.senamhi.gob.pe) and, in particular, the collection of discharge information through runoff gauging in big rivers of the Peruvian Amazon under the Hydrogeodynamics of the Amazon Basin (HyBAm, http://www.ore-hybam.org/) project, a collaboration between SENAMHI and the French Institute of Research for Development (IRD, http://www.ird.fr/).

THE PERUVIAN DRAINAGES

Peruvian hydroclimatology is influenced by the disruption of the large-scale circulation patterns caused by the Andes cordillera, the contrasting oceanic boundary conditions and the landmass distribution (Garreaud *et al*. 2009).

The Pd features small basins with rivers flowing east to west, from the Andes toward the Pacific Ocean (Fig. 1). These basins have bare and steep slopes that favour significant erosion and flooding during very rainy episodes. Weak rainfall along the Pacific coast is related to the large-scale mid tropospheric subsidence over the southeastern subtropical Pacific Ocean, enhanced by the coastal upwelling of cold water. The warming of the air above and the cold sea-surface temperature (SST) result in a cool, moist marine boundary layer of 500–1000 m thickness, capped by a strong temperature inversion (Garreaud

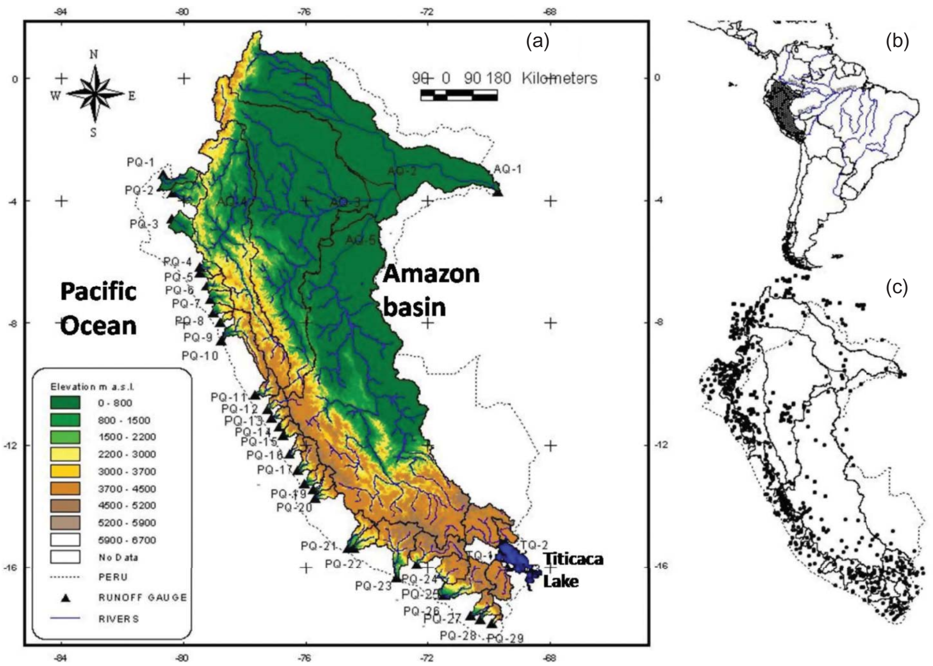

Fig. 1 (a) Elevation of the study area, main rivers, limits of the selected basins in the Pacific, Titicaca and Amazon drainages and location of the runoff gauges (see Table 1). (b) Location of the study zone in South America. (c) Location of the rainfall gauges used in this study.

et al. 2002). In the austral summer, the slight weakening of the southeast Pacific anticyclone and the southward displacement of the Pacific intertropical convergence zone (ITCZ) allow the development of a rainy season. UNESCO (2006) assesses that mean annual rainfall and runoff in Pd are very low, about 274 and 168 mm, respectively, during the 1969–1999 period. However, within the region, rainfall and runoff show significant internal differences. Indeed, rainfall is more abundant along the northern coast and declines towards the south where conditions of extreme aridity occur due to the large-scale subsidence acting in concert with regional factors (Rutllant *et al*. 2003, Garreaud *et al.* 2009).

The Ad is characterized by hot tropical lowlands at near sea level and freezing cold, tropical, high mountains peaking at more than 6000 m a.s.l. elevation. The rivers in the Ad have steep slopes in the western Andean region and very small gradients in the flat eastern lowlands; seldom do such dramatic environmental contrasts lie closer together. Naturally, each of these two realms is subject to different, but in many aspects interrelated, sets of physical, geochemical and biological parameters (ACTO 2005). Very wet conditions are observed in the Amazon basin, due to the convection of moist and hot air that originates from the evapotranspiration of the rainforest and the advection of humid air from the tropical Atlantic. Rainfall is more abundant during the South American monsoon (Zhou and Lau 1998), i.e. in the austral summer, in the southernmost tropical regions and around the autumn equinox towards the Equator, where the seasonal variability is nevertheless very low (Johnson 1976, Espinoza *et al.* 2009b). According to UNESCO (2006), mean rainfall over Ad during the 1969–1999 period was close to 2060 mm year^{-1}, but important spatial variations are observed with a general rainfall decrease toward the tropics (i.e. the south) and toward the Andes as rainfall tends to diminish with altitude, to <1500 mm above 2000 m a.s.l. (Espinoza *et al*. 2009b). However, in the Andes, very high and low rainfall values (between 6000 and 250 mm/year) can be observed at nearby stations due to the leeward or windward position of raingauges (Espinoza *et al*. 2009b).

The Td is located on the Altiplano (southeast of Peru, Fig. 1) and its endorheic drainage is realized from high Andean summits (surpassing 6000 m a.s.l.) with streams flowing towards Lake Titicaca (~3800 m a.s.l.), then the Desaguadero River and finally Poopo and Salar de Coipasa lakes in Bolivia. UNESCO (2006) assesses that, on the Altiplano, mean annual rainfall and runoff during the 1969–1999 period were 813 and 89 mm, respectively. The rainy season is in the austral summer, with a peak in January, and is characterized by intense convective activity combined with moisture advection from the Amazon basin (Aceituno and Montecinos 1993, Chaffaut *et al*. 1998, Vuille *et al*. 1998, Garreaud 1999, Garreaud *et al*. 2003, Vizy and Cook 2007). During the austral winter, the moist eastern flux is replaced by westerly winds, which provide dry air related to the atmospheric stability over the Pacific Ocean. This strong seasonality explains the moderate amounts of annual rainfall. However, locally, around Lake Titicaca, water vapour is more abundant and annual rainfall exceeds 1000 mm/year (Roche *et al.* 1990).

The El Niño Southern Oscillation (ENSO) has opposing influences on inter-annual variability of rainfall and runoff in the northern Pacific drainage and in the Lake Titicaca region (Waylen and Caviedes 1986, Ropelewski and Halpert 1987, Aceituno 1988, Tapley and Waylen 1989, 1990, Rome-Gaspaldy and Ronchail 1998, Vuille *et al*. 2000, Waylen and Poveda 2002, Romero *et al*. 2007, among others). During El Niño, rainfall and runoff are higher than normal in the northern Pd, while it is associated with hydrological drought in Td and over the high Andes. Dramatic rainfall on the coast during El Niño is related to the inversion of the Pacific Walker cell, with enhanced ascendance over the unusually warm waters in the central and eastern Pacific. On the Altiplano, the El Niño drought is associated with a warming of the tropical atmosphere, a strengthening of the westerlies and less advection of moist air from the Amazon basin (Aceituno and Montecinos 1993, Garreaud and Aceituno 2001). Moreover, inter-annual rainfall variability in the southern Amazon basin is negatively related to North Atlantic sea-surface temperatures (NATL SSTs) (Ronchail *et al.* 2002, Yoon and Zeng 2009, Lavado 2010), as well as runoff in the Peruvian Amazonas basin (Espinoza *et al*. 2009a). Warm SST conditions over the northern tropical Atlantic favour convection in this oceanic region and the converse, subsidence, over the southern tropics.

Long-term rainfall and runoff variability have also been observed in Peru. Marengo (1995, 1998) found decreasing runoff trends during the 20th century at some gauging stations located in the northern Pd. These were not natural, being often related to water abstraction for irrigation and domestic usage in the growing cities and farming zones. In contrast, runoff of the high-elevation, upstream Santa River has become more regular as its basin is undergoing glacier retreat (Kaser *et al.* 2003, Mark and Seltzer 2003, Mark *et al*. 2005, Pouyaud *et al*. 2005, Vuille *et al*. 2008a, 2008b, among others). On the Altiplano, a 13-year climatic periodicity is observed in Quelccaya ice-cores (Melice and Roucou 1998) and a recent decrease (since the end of the 1980s) is detected in the level of Lake Titicaca, which acts as a rainfall gauge for the Td region (Rigsby *et al.* 2003). In the Ad, Gentry and Lopez-Parodi (1980) associated upward (downward) trends in maximum (minimum) water levels in Iquitos (AQ-2, see Table 1) during the 1962–1978 period with deforestation, as no clear rainfall change had been observed during the same period. Nordin *et al.* (1982) and Richey *et al*. (1989) discussed these results, as did Rocha *et al*. (1989), who found positive rainfall trends in Iquitos and Pucallpa stations during the 1955–1979 and 1957–1981 periods, respectively. Marengo (2004) and Espinoza *et al*. (2006, 2007, 2009a) suggest that the long-term rainfall evolutions in the north and the south of the basin are in opposition with the Pacific Decadal Oscillation. During the 1990–2005 period, Espinoza *et al.* (2009a) and Espinoza *et al.* (2007), respectively, describe an upward runoff trend in the northern Ad (AQ-3, see Table 2), and a downward runoff trend over the southern Ad (AQ-5, see Table 2).

DATA AND METHODS

This work is based on monthly rainfall and discharge data in 33 basins (29 in Pd, three in Td and two in Ad), during the 1969/70–2003/04 period, with the hydrological year running from September to August (Table 1, Fig. 1). Basin subdivision was made using the Digital Elevation Model (DEM) provided by the National Aeronautics and Space Administration (NASA) through the Shuttle Radar Topography Mission (SRTM – www2.jpl.nasa.gov/srtm). The SRTM data are available at 3 arc second (~90-m resolution). A description of this model is provided by Farr *et al*. (2007).

Monthly rainfall data for 1965 to 2007 are from the SENAMHI network and have been checked by this institute. The Pd and Td data have also been checked by UNESCO (2006), for the 1969–1999 period. Under the HyBAm project, rainfall data over Ad underwent preliminary quality control by Espinoza *et al*. (2009b) for the 1965–2003 period, and by Lavado (2010) for the 2003–2007 period, using the Regional Vector Method (RVM; Hiez 1977, Brunet-Moret 1979, and see the detailed presentation of the method in Espinoza *et al.* 2009b). Rainfall stations are more abundant in Pd and Td (119 stations) and, taking into account its large surface area, less numerous in the Ad (48 stations).

Table 1 Gauging and rainfall stations used in this study. Lat.: latitude; Long.: longitude; Alt.: altitude (m a.s.l.); Dr. area: drainage area (km^2) and Qsp.: specific runoff (L s^{-1} km^{-2}).

Gauging station	River	Code	Lat.	Long.	Alt. (m a.s.l.)	Dr. area (km^2)	Qsp. (L s^{-1} km^{-2})
El Tigre	Tumbes	PQ-1	3.72°S	80.47°W	40	4 802	23.7
El Ciruelo	Chira	PQ-2	4.30°S	80.15°W	250	7 760	14.8
Pte. Ñacara	Piura	PQ-3	5.11°S	80.17°W	119	4 765	5.9
Racarumi	Chancay-Lambayeque	PQ-4	6.63°S	79.32°W	250	2 401	14.2
Batan	Zaña	PQ-5	6.80°S	79.29°W	260	681	11.7
Yonan	Jequetepeque	PQ-6	7.25°S	79.10°W	428	3 354	8.3
Salinar	Chicama	PQ-7	7.67°S	78.97°W	350	3 651	6.8
Quirihuac	Moche	PQ-8	8.08°S	78.87°W	200	1 918	4.7
Huacapongo	Viru	PQ-9	8.38°S	78.67°W	280	941	4.3
Pte. Carretera	Santa	PQ-10	8.97°S	78.63°W	18	11 869	16.9
Yanapampa	Pativilca	PQ-11	10.67°S	77.58°W	800	4 270	10.1
Sayan	Huaura	PQ-12	11.12°S	77.18°W	650	2 896	10.0
Santo Domingo	Chancay-Huaral	PQ-13	11.38°S	77.05°W	697	1 881	9.6
Larancocha	Chillon	PQ-14	11.68°S	76.80°W	120	1 238	4.8
Chosica	Rimac	PQ-15	11.93°S	76.69°W	906	2 339	13.3
La Capilla	Mala	PQ-16	12.52°S	76.50°W	424	2 141	7.0
Socsi	Cañete	PQ-17	13.03°S	76.20°W	330	6 003	8.2
Conta	San juan	PQ-18	13.45°S	75.98°W	350	3 144	3.2
Letrayoc	Pisco	PQ-19	13.65°S	75.72°W	720	3 107	6.8
Los Molinos	Ica	PQ-20	13.92°S	75.67°W	460	2 154	0.5
Bella Union	Acari	PQ-21	15.48°S	74.63°W	70	4 369	3.2
Puente Jaqui	Yauca	PQ-22	15.48°S	74.45°W	214	4 245	2.1
Pte. Ocoña	Ocoña	PQ-23	16.42°S	73.12°W	122	16 646	4.3
Huatiapa	Majes	PQ-24	16.00°S	72.47°W	699	13 651	6.3
Pte. Del Diablo	Chili	PQ-25	16.41°S	71.50°W	236	8 750	1.5
La Pascana	Tambo	PQ-26	16.99°S	71.64°W	281	12 884	2.2
Pte. Viejo	Locumba	PQ-27	17.62°S	70.77°W	550	3 639	0.8
La Tranca	Sama	PQ-28	17.73°S	70.48°W	620	1 993	1.5
Aguas Calientes	Caplina	PQ-29	17.85°S	70.12°W	130	569	1.8
Pte. Ramis	Ramis	TQ-1	15.26°S	69.87°W	385	16 229	4.7
Pte. Huancane	Huancane	TQ-2	15.22°S	69.79°W	386	3 714	5.4
Pte. Ilave	Ilave	TQ-3	16.09°S	69.63°W	385	8 714	4.5
Tabatinga	Amazonas	AQ-1	4.25°S	69.93°W	60	890 308	42.7
Tamshiyacu	Amazonas	AQ-2	4.00°S	73.16°W	105	733 596	44.4
San Regis	Marañon	AQ-3	4.51°S	73.95°W	80	359 910	
Borja	Marañon	AQ-4	4.47°S	77.55°W	450	115 478	
Requena	Ucayali	AQ-5	5.03°S	73.83°W	200	354 316	

In the Amazon basin, they are concentrated in the Andes head basins that are more easily accessible than the lowlands. The kriging interpolation method, which establishes a variogram for each spatial point, was applied to compute the average rainfall in each basin (Oliver and Webster 1990, Deutsch and Journel 1992). The variograms evaluate the influence of the 16 closest stations according to their distance. This method was selected because it takes into consideration a possible spatial data gradient which is very important in a mountainous region.

Monthly runoff data (1969–2004) collected by the SENAMHI in Peru, and by the National Water Agency of Brazil (ANA, http://www.ana.gov.br) for the Tabatinga station (AQ-1), were used. Although it is the largest part of Peru, very few stations are located in Ad and long time series are only available for very large basins that reach almost 1 million km^2. More detailed information about smaller basins is not useful in the present context as their measurements only began during the 1980s or 1990s. In contrast, the basins in Pd and Td are smaller, <20 000 km^2, and have been densely equipped for a long time.

Runoff data homogenization was performed by SENAMHI using double-cumulative techniques. Cross-correlations between all stations were calculated in order to detect highly-correlated stations (at the 99% level) and to fill missing data using linear regression, when less than 5% of the data of a station was missing. On the coast (Pd), two stations on the Santa (PQ-10) and the Ocoña (PQ-23) are downstream barrages, but runoff in all the rivers is

Table 2 Average values and variability of per basin rainfall and runoff, using the hydrological year (September–August), during the 1969–2004 period (36 years), except for PQ-10 (1969–1999, 31-year period for runoff). *P*: rainfall; *Q*: runoff; MAVC: inter-annual variation coefficients; SVC: seasonal variation coefficients and *r*: linear correlation coefficient between rainfall and runoff. Significant values (95% confidence level) are in **bold**. * rainfall only has been analysed. ** not computed.

Code	*P* (mm)	*Q* ($m^3 s^{-1}$)	Qmax ($m^3 s^{-1}$)	Qmin ($m^3 s^{-1}$)	MAVC (*P*)	MAVC (*Q*)	MAVC (Qmax)	MAVC (Qmin)	*r*	SVC	
										P	*Q*
PQ-1	917	114	371	15	0.4	0.6	0.5	0.3	**0.77**	0.8	1.0
PQ-2	1011	115	321	24	0.4	0.6	0.7	0.6	**0.57**	0.7	0.8
PQ-3	618	28	120	0	0.8	1.5	1.2	3.3	**0.96**	1.3	1.3
PQ-4	722	34	91	7	0.4	0.3	0.4	0.4	**0.79**	0.7	0.7
PQ-5	750	8	22	2	0.7	0.6	0.9	0.4	**0.89**	0.8	0.7
PQ-6	681	28	97	2	0.9	0.6	0.6	0.7	**0.75**	0.9	1.0
PQ-7	744	25	113	2	0.4	1.0	1.1	0.8	**0.93**	0.9	1.2
PQ-8	517	9	35	0	0.4	0.9	1.1	1.2	**0.90**	0.9	1.1
PQ-9	583	4	19	0	0.4	1.3	1.3	1.2	**0.68**	0.7	1.4
PQ-10	489	201	550	49	0.2	0.4	0.4	0.3	0.36	0.7	0.7
PQ-11	521	43	115	12	0.3	0.3	0.4	0.5	**0.59**	0.9	0.6
PQ-12	493	29	85	10	0.3	0.4	0.6	0.3	**0.61**	0.9	0.8
PQ-13	460	18	61	5	0.3	0.4	0.6	0.4	**0.75**	1.1	0.9
PQ-14	455	6	18	2	0.3	0.4	0.4	0.9	**0.47**	1.1	0.8
PQ-15	515	31	70	17	0.2	0.3	0.4	0.3	**0.52**	1.0	0.5
PQ-16	409	15	59	1	0.3	0.5	0.5	0.6	**0.65**	1.1	1.2
PQ-17	407	49	155	9	0.2	0.5	0.7	0.3	**0.64**	1.0	0.9
PQ-18	184	10	45	0	0.3	0.7	0.9	1.2	**0.57**	1.3	1.2
PQ-19	500	21	82	2	0.3	0.5	0.7	0.7	**0.44**	0.9	1.1
PQ-20	357	1	3	0	0.4	0.5	0.5	**	**0.43**	1.1	1.4
PQ-21	240	14	72	0	0.4	0.8	0.8	3.0	**0.49**	1.1	1.5
PQ-22	237	9	45	0	0.4	0.8	0.9	0.4	**0.50**	1.3	1.4
PQ-23	487	71	244	17	0.3	0.5	0.5	0.6	**0.50**	1.1	0.9
PQ-24	463	86	291	26	0.3	0.3	0.4	0.2	**0.75**	1.1	0.9
PQ-25	305	13	45	6	0.3	0.7	1.0	0.6	**0.64**	1.2	0.7
PQ-26	281	28	90	11	0.4	0.6	1.0	0.5	**0.62**	1.3	0.7
PQ-27	230	3	5	2	0.4	0.2	0.5	0.3	**0.40**	1.4	0.3
PQ-28	164	3	12	1	0.5	0.6	0.7	1.0	**0.82**	1.5	1.2
PQ-29	144	1	2	0	0.5	0.3	0.6	0.3	**0.65**	1.4	0.5
TQ-1	773	76	260	8	0.2	0.3	0.3	0.4	**0.82**	0.9	1.1
TQ-2	729	20	78	2	0.2	0.4	0.5	0.5	**0.86**	0.8	1.1
TQ-3	620	39	172	5	0.2	0.5	0.6	0.5	**0.78**	0.9	1.2
AQ-1	1913	38044	53710	22545	0.1	0.1	0.1	0.2	**0.82**	0.2	0.3
AQ-2	1701	32605	49238	16603	0.1	0.1	0.1	0.2	**0.60**	0.2	0.3
AQ-3*	1747				0.1					0.5	
AQ-4*	1463				0.1					0.3	
AQ-5*	1496				0.1					0.2	

perturbed by small water captures. In the Rímac valley, discharge has been corrected, taking off the flow captured from the Mantaro River in the Amazon basin. The "natural" Rímac discharge is very low (about 30 m^3/s), and the transfer of water from the Mantaro to the Rímac River is essential for supplying Lima's population (about nine million people).

Annual maximum and minimum monthly runoff (Qmax and Qmin, respectively) complement the mean annual runoff (Qmean). They are the monthly runoff values of the months with the highest and lowest runoff values respectively. The specific runoff of the rivers was computed in order to eliminate the relationship between runoff and basin size.

Seasonal variation coefficients (SVC) were calculated using mean monthly rainfall and runoff and their standard deviation. Likewise, multi-annual variation coefficients (MAVC) were computed using annual rainfall and runoff values.

The trend in the hydrological series was evaluated using the non-parametric Mann-Kendall test that is based on range probability of the data occurrence order (Mann 1945, Kendall 1975) and is considered an excellent tool (Zhang *et al*. 2001, Burn and Elnur 2002).

In addition, the Pettitt non-parametric test for mean-change measurement in temporal hydrological annual series was applied (Pettitt 1979). Considered as one of the most complete tests for identifying mean-change (Kundzewicz and Robson 2004), it is based on changes in the range of the values subdivided into sub-series. The significance level (α) is the probability that a test detects trend or other change when none is present (Robson *et al*. 2000). In this study, the null hypothesis in statistical tests is rejected using $\alpha = 0.05$.

Several regional climatic indexes, provided by the Climatic Prediction Centre of the National Oceanic and Atmospheric Administration (CPC-NOAA, http://www.cdc.noaa.gov/), were used to understand the time variability of rainfall and runoff. The Southern Oscillation Index (SOI) is the standardized pressure difference between Tahiti and Darwin. Monthly SSTs are provided for the northern tropical Atlantic (NATL, 5–20°N, 60–30°W) and the southern tropical Atlantic (SATL, 0–20°S, 30°W–10°E). The standardized SST difference between the NATL and SATL was computed to determine the SST gradient.

Finally, the management of rainfall and runoff databases, as well as the calculation of the average rainfall in the basins, was carried out using the HYDRACCESS software, developed within the framework of the HyBAm project (Vauchel 2005).

SPATIAL AND SEASONAL VARIABILITY OF RUNOFF AND RAINFALL

Mean annual rainfall values (1969–2004) in 167 stations, interpolated using the kriging method, are displayed in Fig. 2. They feature a strong contrast between the rainy eastern lowlands in the Amazon basin (more than 1500 mm/year) and much drier conditions in the Andes and almost no rainfall in the basins of the Pacific coast, except in the extreme north. When integrating rainfall by basin (Table 2), annual values vary from about 144 mm year^{-1} in the southernmost Pacific coast basin, to 1900 mm in the Tabatinga basin.

Along the Pacific coast, mean rainfall per basin increases regularly as latitude diminishes (i.e. from south to north), from 144 mm/year (PQ-29) to nearly 1000 mm/year in the north (Table 2 and Fig. 3(a)).

The specific runoff tends to increase consistently towards the north (Fig. 3(b)), ranging from less than 1 L s^{-1} km^{-2} in the south to 24 L s^{-1} km^{-2} in the northernmost Tumbes basin (Table 1); but the specific runoff increase is not as regular as the rainfall increase. Indeed, it seems that the relation between specific runoff and latitude is organized within some sets of stations. These groups of stations, from PQ-1 to PQ-3, from PQ-4 to PQ-9, from PQ-10 to PQ-20 and finally from PQ-21 to PQ-29 are lined up in Fig. 3(b).

Along the Pacific coast, there is no clear relationship between annual *in situ* rainfall and altitude (Fig. 4(a)). Near null or very low rainfall values are often observed near sea-level. Above the inversion layer, rainfall is generally more abundant (Dollfus 1964, Johnson 1976) but very little rainfall may also be recorded at altitude, probably due to the lee wind exposure of the stations. The highest rainfall, up to 2000–2500 mm/year, is observed at between 1000 and 3000 m, but very high rainfall variability characterizes this altitudinal range. Finally, above 3000 m, rainfall increases from less than 500 to 750 mm/year.

In Td annual rainfall varies from 400 to 800 mm per year below 4000 m, and does not exceed 600 mm above this altitude (Fig. 4(b)). As a consequence of the moderate rainfall, specific runoff is about 5 L s^{-1} km^{-2} (Table 1).

In the Ad, in contrast, *in situ* rainfall is abundant and, as a consequence, specific runoff is greater than 40 L s^{-1} km^{-2} in Tabatinga and Tamshiyacu (Table 1). Rainfall is very high near Equator (>2500 mm/year) and local maximum and minimum rainfall are noticeable in Fig. 2. In particular, very high annual rainfall (>6000 mm/year) is recorded in regions where the concave form of the Andes favours convergence (Borja region), in valleys open to the north and oriented toward the humid northwestern winds (High Ucayali and Pachitea valleys), and along massive relief with a northward exposure. They contrast with less rainy regions such as the high Huallaga valley that is located on a lee side and is consequently protected from moist air advection. In the Amazon basin, local rainfall tends to increase as altitude diminishes (Fig. 4(c)). Abundant rainfall of ~2500 mm/year is related to the moist warm air and to the release of high quantities of water vapour over the first eastern slope of the Andes. In contrast, annual rainfall is often less than 1000 mm/year above 500 m elevation. Similar situations regarding rainfall–topography relationships have been described in the Amazon basin as a whole by Johnson (1976), Figueroa and Nobre (1990) and Espinoza *et al.* (2009b), in Ecuador, Colombia and Venezuela by Laraque *et al.* (2007), Poveda (2004) and Pulwarty *et al*. (1992), respectively, and in Bolivia by Guyot (1993) and Ronchail and Gallaire (2006).

Monthly rainfall per basin and runoff values, expressed as a percentage of the hydrological annual

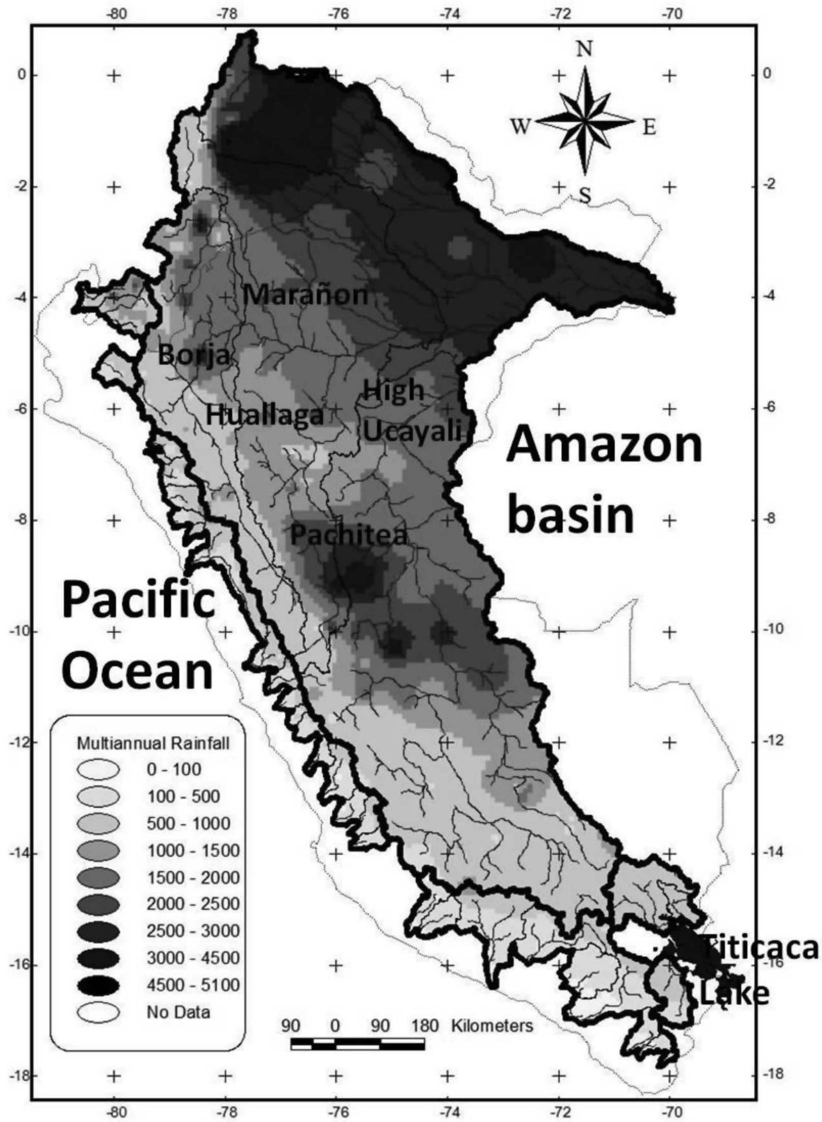

Fig. 2 Interpolated mean annual rainfall values (mm) for the 1970–2004 period, over the (a) Pacific (Pd), Amazonas (Ad) and Titicaca (Td) drainages, using *in situ* data.

values, are presented in Fig. 5 for all the gauging stations. Along the Pacific coast (Pd) and in Td, there is a pronounced annual cycle in rainfall, with a rainy season during the austral summer and a dry season in winter. On the coast, the peak of the rainy season changes with latitude. South of 12°S, from PQ-14 to PQ-29, there is a January–February peak consistent with the occurrence of a rainfall peak in the tropical Andes that provides most of the water in these basins. From PQ-14 to the north of the Peruvian coast (near the Equator) the rainfall peak is more acute and occurs in March, i.e. during the equinox period. Moreover, the dry season diminishes from south to north; the period without rainfall or with very little rainfall begins as soon as April in the south and in June near the Equator. The strong seasonal variability is also illustrated by the seasonal coefficient of variation (SCV) values. They are always higher than 0.7 (Table 2) and decrease from the southern to the northern Pacific coast. SCV values as high as 1.5 are computed for the southern stations. Evidently, there is a strong seasonality in discharge in the coastal basins (Table 2). This is enhanced by the fact that some small rivers, in the north as well as in the south of the Pacific coast, are intermittent and are characterized by null or near null low-level flow in the austral winter. Moreover, it is noticeable that in some basins the seasonal discharge variability is higher than rainfall variability, while the contrary is true in other basins where runoff is regulated by man (for

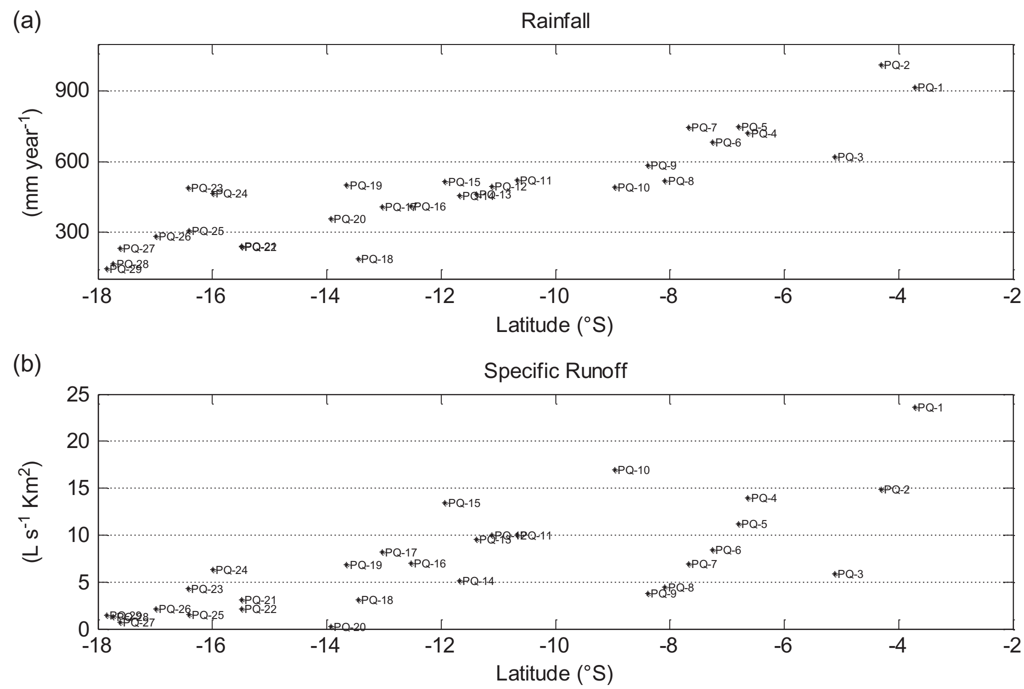

Fig. 3 Relationships between latitude and: (a) mean multi-annual rainfall per basin (mm), and (b) specific runoff (L s^{-1} km^2), in the Pacific drainage. Labels and locations of the stations are described in Fig. 1 and Table 1.

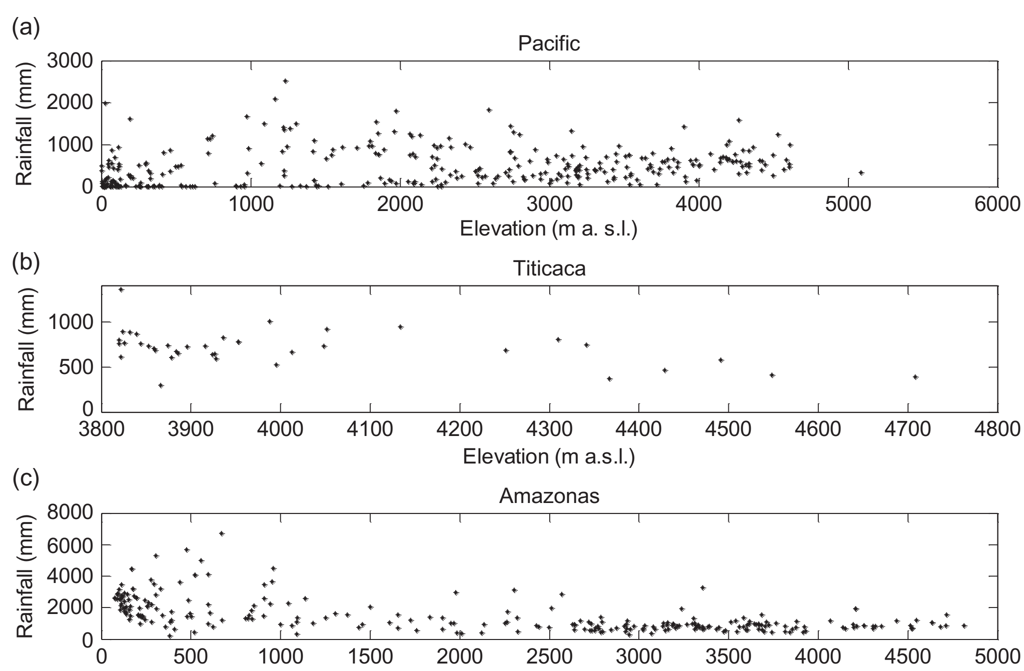

Fig. 4 Relationships between altitude (m a.s.l.) and mean multi-annual *in situ* rainfall (mm) during the 1970–2004 period in: (a) the Pacific drainage, Pd; (b) the Titicaca drainage, Td; and (c) the Amazonas drainage, Ad.

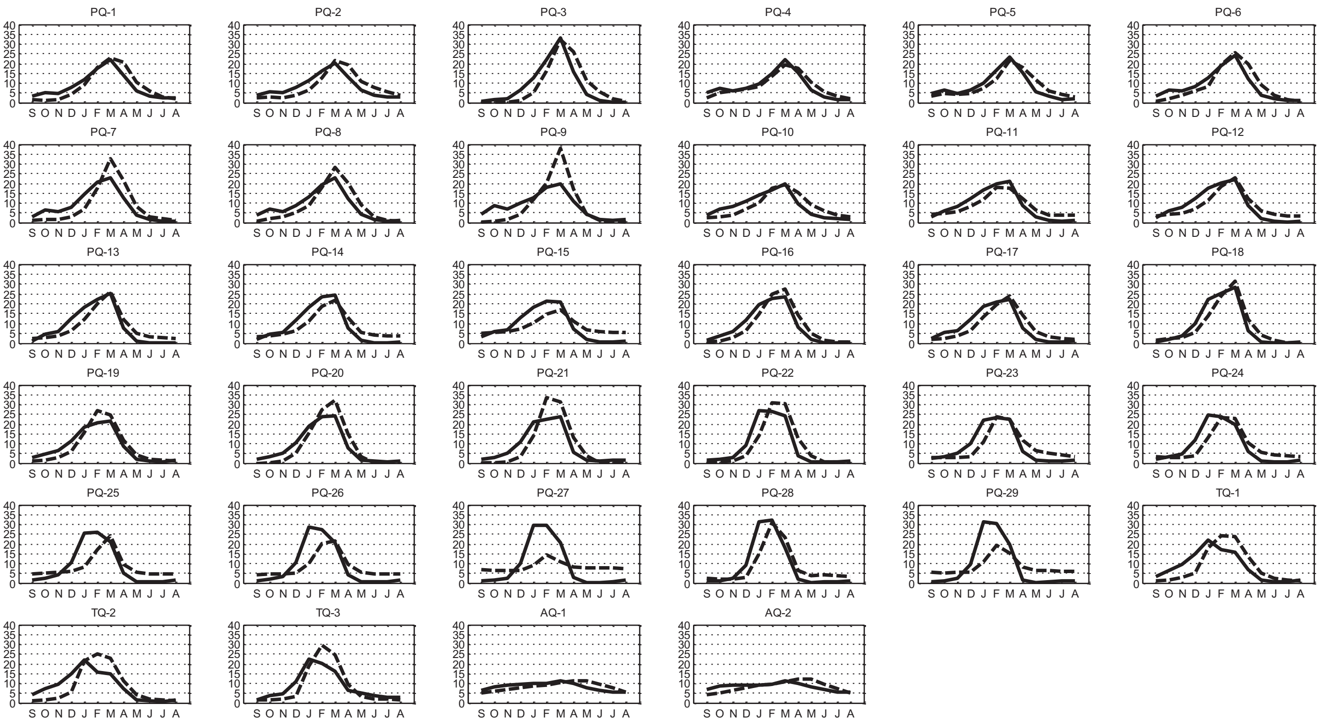

Fig. 5 Mean monthly per basin rainfall and runoff in percentage (ratio between monthly and mean annual values for runoff and ratio between monthly and total annual values for rainfall) in the selected basins in Peru (see Fig. 1(a) and Table 1). The solid lines represent rainfall and the dashed lines runoff.

instance from PQ-11 to PQ-15, around Lima, and in the southernmost basins).

On the tropical Altiplano (Td), there is a sharp contrast between a rainy season in the austral summer, with a peak in January, and a very dry season from May to August. Consequently, the seasonal variability of rainfall and discharge is important and SCV values are about 1 (Table 2). In contrast, in the Ad, rainfall is abundant all year round, with a small summer maximum during the South American monsoon and a minimum in August. The seasonal rainfall and discharge coefficients of variation are much lower than in Pd and Td, i.e. 0.2 for rainfall per basin and 0.3 for discharge (Table 2).

In the small Pd basins there is an immediate runoff response to rainfall, with rainfall and discharge peaks in March and low values in the austral winter (Fig. 5). But, towards the south there may be a month's lag between the maximum rainfall and the high flow runoff. In the Sama basin PQ-28, for instance, which is well-known for its dryness and very high solar radiation, the lag may be explained by the delay between rainfall, the soil moistening after the dry season and runoff. In Td, there is a lag of about one month between rainfall (January) and runoff (February–March) peaks. As the sizes of the Amazonian basins are huge, there are two-month lags between peaks in rainfall (March) and runoff (May), as in Tabatinga gauging station (AQ-1).

INTER-ANNUAL VARIABILITY OF RAINFALL AND DISCHARGE

Standardized 1970–2005 annual runoff and rainfall per basin are plotted for some stations (Fig. 6), showing that rainfall and runoff present similar variability. This is confirmed by the correlation between rainfall and runoff (Table 2). The coefficients of correlation range between 0.4 and 0.96; that means that rainfall explains 16% of discharge variability in some basins and 92% in others. The correlation is low in some coastal basins (PQ-14, PQ-15, from PQ-18 to PQ-23, PQ-27) and not significant in the Santa basin (PQ-10). This may be due to various reasons, natural or anthropogenic. The availability of underground water may sustain low flow runoff when rainfall is missing (Mark *et al.* 2010); its absence may emphasize the seasonal and inter-annual variability. Glacier-ice melting in upstream valleys, particularly important at the beginning of the rainy season when the glaciers are "dirty" and the albedo is very low (Wagnon *et al.* 1999, 2001, Sicart 2002) may also

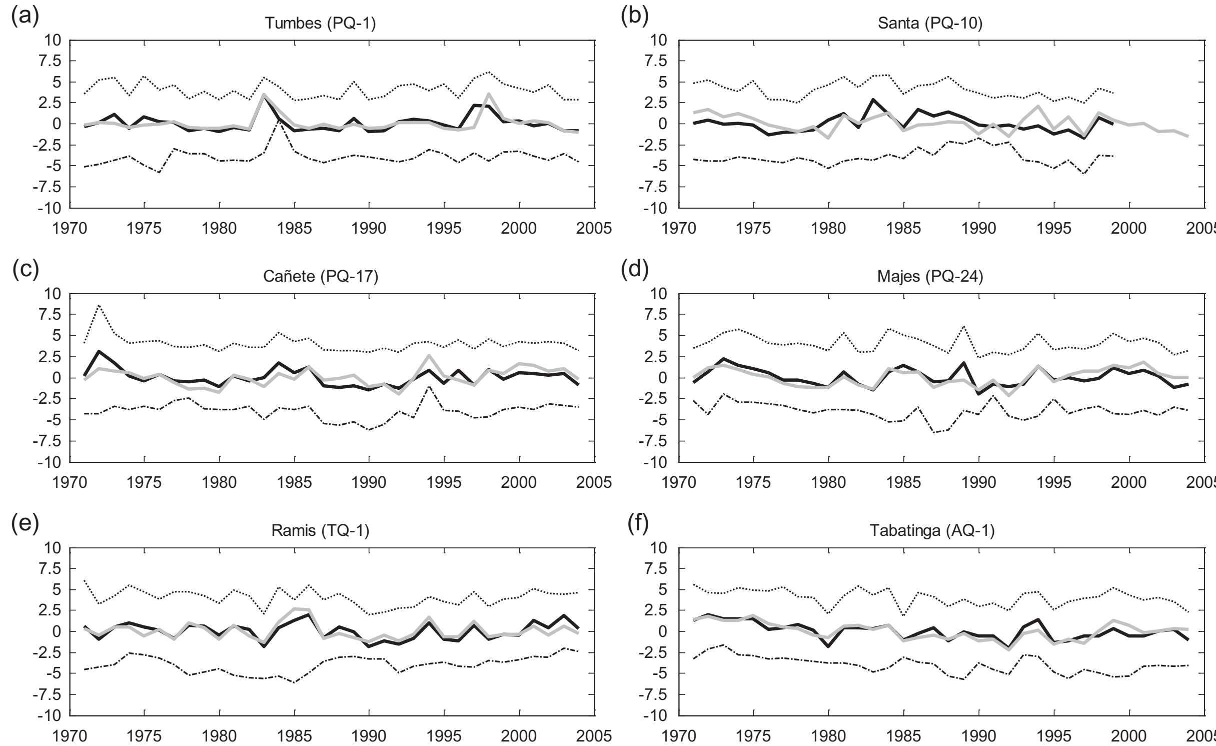

Fig. 6 Annual hydrological series (September–August) for: (a) the Tumbes River (PQ-1), (b) the Santa basin (PQ–10), (c) the Cañete basin (PQ-17), (d) the Majes basin (PQ-24), (e) the Ramis basin (TQ-1) and (f) the Tabatinga basin (AQ-1). Black lines represent: mean annual runoff; grey lines: total annual per basin rainfall; dotted lines: maximum runoff; and dashed lines: minimum runoff. Values are standardized and are corrected by coefficients in order to avoid confusion between the different lines. The coefficients are 4 for maximum runoff, 0 for mean runoff and –4 for minimum runoff.

sustain the runoff. This may explain some disconnection between rainfall and discharge in the Santa River (PQ-10) located downstream of the Cordillera Blanca glaciers (Fig. 6). Indeed, Mark *et al*. (2005) estimate that nearly 40% of the upper Rio Santa discharge at Huallanca (which comprises 40% of the Rio Santa basin at Puente Carretera—PQ-10) is glacier melt. The nature of the link between rainfall and discharge can also be driven by barrages or water abstraction/deviation (for irrigation, hydroelectricity or city water supply), as in the case of the Rímac basin (PQ-15) that provides water towards the city of Lima and of the Santa basin (PQ-10) that provides water for hydroelectricity and irrigation purposes.

Figure 7 presents the gross runoff and rainfall per basin and points out a strong inter-annual variability along the coast that culminates in the Piura River (PQ-3) where the rainfall multi-annual variation coefficient (MAVC) reaches 0.8 and where discharge MAVC surpasses 1 and attains 3.3 for Qmin (Table 2). The highest values are often observed in the north, in association with ENSO events that sometimes quintuple annual rainfall. Dramatic rainfall and runoff anomalies were observed during the last two extreme ENSO events (1982–1983 and 1997–1998) (Figs 6(a) and 7(a)). However, discharge variability is not spatially even: some basins with a very strong inter-annual variability, such as Piura (PQ-3), are next to others that display a very low variability (Chira—PQ-2 or Chancay-Lambayeque—PQ-4). These differences are probably due to local groundwater and/or water exploitation conditions. On the southern Pacific coast, high runoff MAVC are consistent with rainfall variability and may be accentuated by the lack of outflow during some very dry years, i.e. by the intermittency of the rivers (Fig. 7(b)).

In Td and Ad, correlation between rainfall and runoff is generally high, as runoff does not stop seasonally and is not perturbed by anthropogenic activities (Table 2). In Tamshiyacu (AQ-2), the rather weak correlation ($r = 0.6$) between rainfall and runoff may be related to the poor availability of raingauge data in the rainy Marañon sub-basin of the Amazon (see Fig. 1(c)). A weak inter-annual variability in the Ad gives very low MAVC, about 0.1 for rainfall, while they are a little higher in the Td (Table 2 and see Tabatinga and Ramis in Figs 7(d) and (c)).

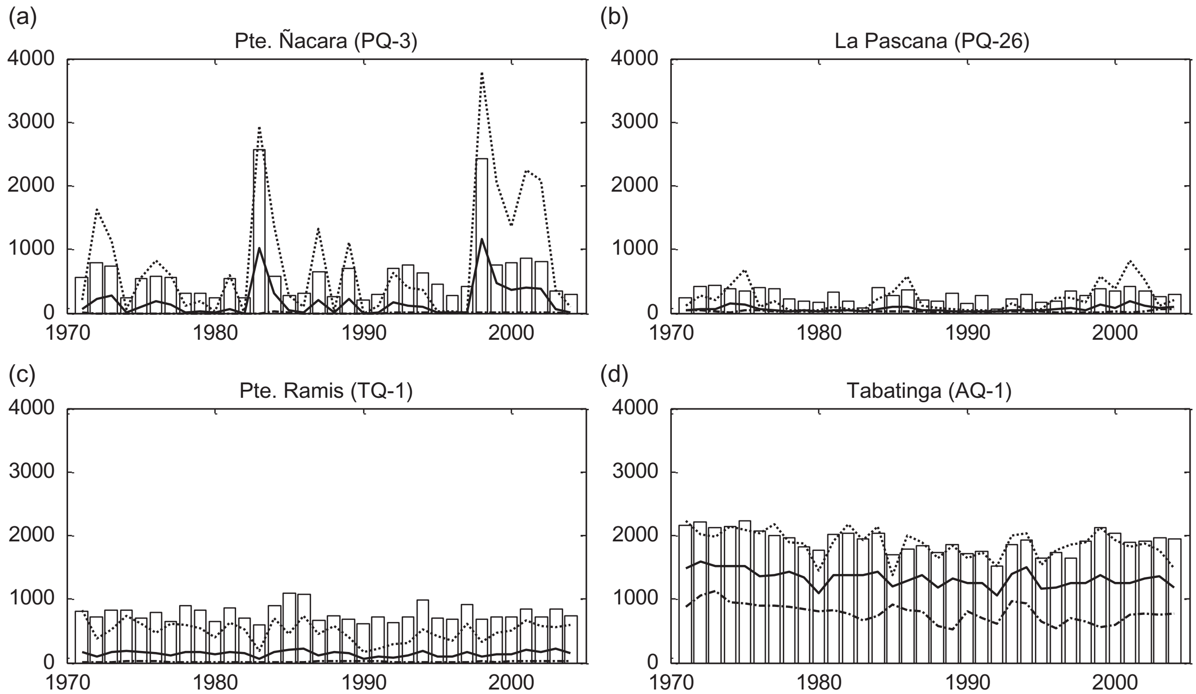

Fig. 7 Annual hydrological series (September–August): (a) Pte Ñacara (PQ-3); and (b) La Pascana (PQ-26) in the Pacific drainage; (c) Pte Ramis (TQ-1) in the Titicaca drainage; and (d) Tabatinga (AQ-1) in the Amazonas drainage. Bars represent: total annual per basin rainfall; solid line: mean annual runoff; dotted lines: maximum runoff; and dashed lines: minimum runoff. Values are in mm.

In summary, the Pd, shows greater rainfall and runoff variation than Td and Ad, at the seasonal and inter-annual time scales. This is particularly visible in Figs 8(a) and (c) where MAVC of runoff and rainfall, respectively, are plotted against seasonal coefficients (SVC). The Titicaca and Amazon basins are located near the origin of the graph, while the Pacific basins are generally located higher in the graph, occupying a wide range of values and demonstrating a large variety of natural and anthropogenic situations. Figures 8(b) and (d) show the ratio MAVC/SVC in runoff and rainfall in Pd *vs* latitude. As already mentioned, a clear difference is evident between northern and southern stations, the northern Pd basins showing the highest inter-annual variation in rainfall and runoff, when compared to seasonal variation, due to the strong hydrological impacts of extreme El Niño events on the northern coast. Thus, during the last strong El Niño events (1982–1983 and 1997–1998) rainfall and runoff changes (related to the 1969–2004 mean) in the northern Pd were approximately +250% (PQ-1, PQ-2, PQ-3 and PQ-4, northward of 6.5°S.).

Another set of basins, in the southernmost coastal region, experiences a strong inter-annual runoff variability, which is not always observed in rainfall. This may be due to the use of abundant rainfall gauges in the Andes to compute rainfall over the basins when compared to the number of rainfall gauges along the coast. Yet, we know that rainfall variability is lower in the Andes than on the coast.

RUNOFF AND RAINFALL CHANGES AND TRENDS

The long-term variability of rainfall and runoff is analysed through break and trend analysis. The years of significant mean changes in rainfall and runoff in the Peruvian basins are presented in parentheses in Table 3, together with information about trend in the series.

The main result is a change in rainfall and runoff in the mid-1980s in the two Amazonian basins, with rainfall and runoff decreases afterwards that have already been described by Espinoza *et al.* (2009a). The decrease is particularly important in Qmin since 1987, principally in Tamshiyacu (from 18 911 $m^3 s^{-1}$ in 1969 to 15 390 $m^3 s^{-1}$ in 2006). In this station, the absence of significant rainfall decrease may be due to uncertainties about rainfall estimation related to the low rainfall data availability in the Marañón sub-basin (Fig. 2). In Tabatinga, the Qmin decrease (from

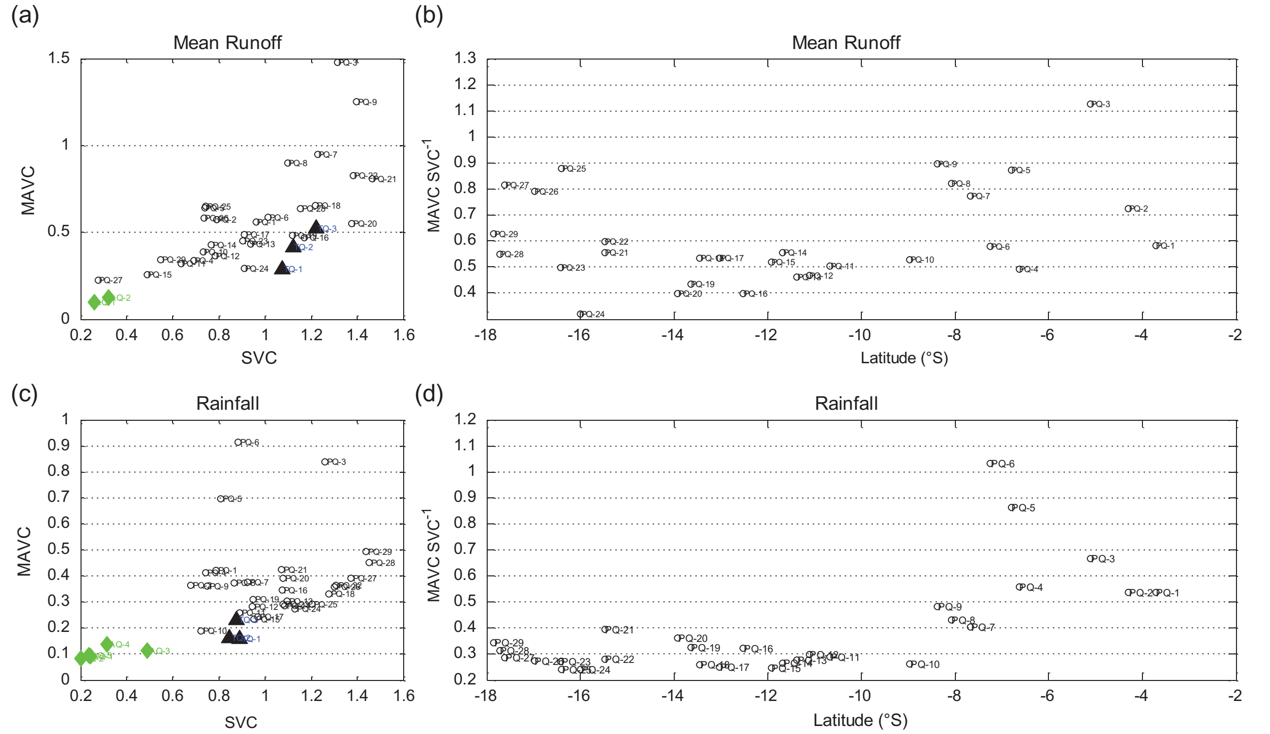

Fig. 8 Relationships between multi-annual variation coefficients (MAVC) and seasonal variation coefficients (SVC) for: (a) runoff and (c) per basin rainfall, in Peru; and the MAVC/SVC ratio as a function of latitude for stations located in the Pacific drainage: (b) runoff and (d) per basin rainfall. Black circle: Pacific drainage stations; grey diamond: Amazon drainage stations; black upward triangle: Titicaca drainage stations.

25 316 $m^3 s^{-1}$ in 1969 to 22 126 $m^3 s^{-1}$ in 2006) is associated with a rainfall diminution.

In the Td, in contrast, there is a significant increase in minimum runoff, from 6 $m^3 s^{-1}$ in 1969 to 13 $m^3 s^{-1}$ in 2006, in the Ramis basin, with a change in 1986 that is not related to a change in annual rainfall. The analysis of seasonal rainfall, in particular during the end of the rainy season and during the low flow season, would be useful to understand this feature.

Along the Pd, half of the stations present changes and trends, mainly in minimum runoff. The signals differ from one station to another, occur at very different dates from the 1970s until the late 1990s and are not related to change in annual rainfall. As there is no uniform regional signal, we can hypothesize that the atmospheric circulation and rainfall are not the cause of these changes. They may be related to constructions dedicated to sustaining low-flow "dam intakes" when the change is positive, and to water withdrawal when the change is negative. Positive trends are found in the Chillon (PQ-14), Rímac (PQ-15), Yauca (PQ-22) and Sama (PQ-28). The runoff of the Chillon and Rímac rivers is mostly diverted to urban use for the city of Lima that, according to the 2007 census from the National Institute of Statistic and Informatics of Peru, INEI (http://www.inei.gob.pe), gathers 30.8% of the total Peruvian population (about 28 million). Thus, the increase in minimum runoff is due to runoff control in the high rainfall zones of these basins, which involve many reservoir systems. Negative trends are observed in the rivers Viru (PQ-9), Pativilca (PQ-11), Huaura (PQ-12), Acari (PQ-21) and Ocoña (PQ-23).

There is no trend in the big Santa River (PQ-10); on the one hand, its upper basin benefits from the melting of the Cordillera Blanca Glacier (Mark and Seltzer 2003, Mark *et al.* 2005, Pouyaud *et al.* 2005) but, on the other hand, its water is intensely exploited for export agricultural production and hydro-electricity.

RELATIONSHIPS BETWEEN OCEAN–ATMOSPHERE INDICES AND PERUVIAN HYDROLOGY

In order to find explanations for the inter-annual and long-term variability of runoff and rainfall per

Table 3 Changes and trends in runoff and per basin rainfall. Years of change are in parentheses when the Pettit test is significant at the 95% level. Statistical trends are computed using the Mann-Kendall test for runoff (maximum, mean and minimum) and rainfall annual series (1969–2004 period) except for PQ-10 (1969–1999 for runoff). NEG: significant negative trends (95% confidence level); **POS**: significant positive trends (95% confidence level); nt: no trend; ** not computed.

Code	Trend (YC)			
	Maximum runoff	Mean runoff	Minimum runoff	Rainfall
PQ-1	nt	nt	nt	nt
PQ-2	nt	nt	nt	nt
PQ-3	nt	nt	nt (1991)	nt
PQ-4	nt	nt	NEG (1990)	nt
PQ-5	nt	nt	NEG	nt
PQ-6	nt	nt	nt	nt (1991)
PQ-7	nt	nt	nt	nt
PQ-8	nt	nt	nt	nt
PQ-9	nt	nt	NEG (1976)	nt
PQ-10	nt (1989)	nt	nt	nt
PQ-11	nt	nt	NEG (1980)	nt
PQ-12	nt	nt	NEG (1988)	NEG
PQ-13	nt	nt	nt (1988)	nt
PQ-14	nt	nt	**POS (1994)**	nt
PQ-15	nt	nt	**POS (1994)**	NEG
PQ-16	NEG	nt	Nt	nt (1992)
PQ-17	nt	nt	Nt	nt
PQ-18	nt (1976)	nt	Nt	nt
PQ-19	nt (1988)	nt	**POS (1991)**	nt (1992)
PQ-20	NEG	nt	**	nt
PQ-21	nt	nt	NEG (1982)	**POS (1992)**
PQ-22	nt	nt	**POS (1986)**	nt
PQ-23	nt	nt	NEG (1989)	nt
PQ-24	nt	nt	nt	nt
PQ-25	nt	nt	nt	nt
PQ-26	nt	nt	nt	nt
PQ-27	nt	nt	nt	nt
PQ-28	nt	nt	**POS (1997)**	nt
PQ-29	nt	nt	nt	nt
TQ-1	nt	nt	**POS (1986)**	nt
TQ-2	nt	nt	nt	nt
TQ-3	nt	nt	nt	nt
AQ-1	NEG (1984)	NEG (1984)	NEG (1987)	NEG (1984)
AQ-2	NEG (1984)	NEG (1987)	NEG (1987)	nt (1978)
AQ-3				nt
AQ-4				nt
AQ-5				nt

basin, the hydrological series have been correlated to ocean–atmosphere indices, such as the Southern Oscillation Index (SOI), and Atlantic indexes constructed using sea-surface temperature (SST) in the southern and northern tropical Atlantic Ocean. These indexes were chosen because coastal Peru is a key region for ENSO phenomena (Francou and Pizarro 1986, Aceituno 1988, Tapley and Waylen 1990, Kane 1999, among others), and because the tropical Atlantic SST controls the location of atmospheric ascendance and subsidence over the Atlantic Ocean and South America, the strength of the trade winds and water vapour advection from the Atlantic to the South America tropics (Marengo 2004, Garreaud *et al.* 2009). Moreover, Espinoza *et al.* (2009b) showed that the SSTs in the northern tropical Atlantic are significantly correlated with discharge in the western Amazonian rivers.

Correlations values using the Mann-Kendall test are reported in Table 4. They are often low, explaining, at best, 25–30% of the hydrological series variability. Correlations between minimum runoff and ocean–atmosphere indexes were not considered as reliable, as they can be influenced by human activities, ice melting and the intermittency of the rivers to a much greater extent than Qmean and Qmax,

In the north of the Pd, the expected negative relationships between ENSO and rainfall or runoff are not observed, as heavy rainfall is not observed during all El Niño events but mainly during extreme episodes (1982/83 and 1997/98, see Fig. 7). In the south, the ENSO signal is similar to that observed usually in the Andes, as most of the rainfall in the basins comes from the Andes. The same positive signal is observed in Qmean and Qmax values in all the southern basins, indicating that runoff is lower than usual during El Niño. Moreover, rainfall, Qmean and Qmax in all the southern basins (from PQ-11 for rainfall and PQ-16 for runoff, to PQ-29) are negatively related to the SST gradient in the tropical Atlantic (NATL–SATL). This means that runoff is higher when the southern tropical Atlantic is warmer than usual and/or the northern tropical Atlantic is cooler than usual. Once again, this relationship may represent the link between Atlantic SST and hydrology in the Andes as the water comes from this region. A recent study by Herreros *et al*. (2009) is in agreement with this result.

In the Td, rainfall is usually described as lower during El Niño, but this signal is weak and significant only in the Ramis basin rainfall (TQ-1) and in the mean and maximum discharge of the Huancane River (TQ-2). As observed on the southern coast, there is a negative relationship between NATL, or the Atlantic SST gradient, and hydrological series, but it is rather weak and not all the basins or all the variables are affected.

In Tabatinga, in the Ad, rainfall and runoff are positively related to SOI, with less rainfall and lower mean and maximum runoff during El Niño. Thus, in the Ad, there is a negative signal between NATL

Table 4 Mann-Kendall coefficients between hydrological time series (maximum, mean and minimum runoff and per basin rainfall) and large-scale circulation indexes (SOI: Southern Oscillation Index, NATL: North Atlantic SST, N-S: NATL–SATL SSTs). Significant values (95% confidence level) are underlined (negative) or bold (**positive**). ** not computed.

Code	Maximum runoff			Mean runoff			Minimum runoff			Rainfall		
	SOI	NATL	N-S	SOI	NATL	N-S	SOI	NATL	N-S	SOI	NATL	N-S
PQ-1	0.19	−0.31	−0.12	0.12	−0.42	−0.22	0.08	−0.46	−0.16	**0.29**	−0.26	−0.13
PQ−2	−0.10	−0.05	−0.01	−0.08	−0.12	−0.04	−0.07	0.03	−0.05	−0.06	−0.16	−0.10
PQ−3	0.11	−0.19	−0.22	0.02	−0.29	−0.30	0.13	−0.40	−0.30	−0.06	−0.16	−0.10
PQ-4	−0.06	−0.11	−0.08	−0.05	−0.12	−0.13	−0.09	0.10	−0.04	−0.13	−0.02	−0.01
PQ-5	0.08	−0.13	−0.18	0.13	−0.20	−0.25	**0.27**	−0.43	−0.36	0.13	0.03	−0.09
PQ-6	−0.07	−0.16	−0.11	0.05	−0.20	−0.16	**0.38**	−0.40	−0.30	0.01	−0.07	−0.12
PQ-7	0.03	0.00	−0.09	0.10	−0.12	−0.23	0.21	−0.34	−0.27	−0.09	0.08	0.01
PQ-8	0.05	−0.10	−0.09	0.09	−0.15	−0.21	**0.39**	−0.40	−0.34	0.10	−0.10	−0.11
PQ-9	0.12	−0.09	−0.14	0.11	−0.10	−0.19	**0.38**	−0.29	−0.44	0.09	−0.04	−0.12
PQ-10	0.10	−0.05	−0.09	0.11	−0.06	−0.12	0.18	−0.30	−0.27	0.19	−0.17	−0.21
PQ-11	0.12	−0.01	−0.14	0.03	0.02	−0.21	0.08	−0.04	−0.25	0.17	−0.22	−0.33
PQ-12	0.07	−0.11	−0.19	0.15	−0.21	−0.21	0.24	−0.44	−0.10	0.22	−0.21	−0.28
PQ-13	0.01	−0.25	−0.19	0.15	−0.31	−0.31	0.20	−0.46	−0.31	0.17	−0.35	−0.35
PQ-14	0.04	−0.22	−0.19	0.11	−0.18	−0.26	0.13	−0.20	−0.19	0.14	−0.16	−0.32
PQ-15	0.08	−0.17	−0.13	0.05	−0.12	−0.17	0.00	0.10	0.04	0.18	−0.26	−0.33
PQ-16	0.09	−0.16	−0.09	0.02	−0.06	−0.16	−0.01	0.23	0.05	0.20	−0.29	−0.32
PQ-17	0.25	−0.50	−0.32	0.23	−0.43	−0.46	**0.29**	−0.24	−0.32	0.21	−0.02	−0.25
PQ-18	0.13	−0.24	−0.23	0.11	−0.20	−0.22	0.00	−0.22	−0.03	0.19	−0.15	−0.41
PQ-19	**0.33**	−0.46	−0.44	**0.28**	−0.39	−0.52	0.24	−0.33	−0.43	0.12	−0.24	−0.32
PQ-20	0.18	−0.12	−0.25	0.16	−0.16	−0.35	−0.07	−0.09	−0.18	0.13	−0.01	−0.29
PQ-21	0.25	−0.50	−0.32	0.22	−0.42	−0.45	**	**	**	**0.26**	−0.16	−0.34
PQ-22	0.13	−0.24	−0.26	0.15	−0.18	−0.28	0.10	0.01	0.39	0.22	0.03	−0.24
PQ-23	0.10	−0.22	−0.27	0.15	−0.16	−0.32	−0.05	−0.02	−0.25	0.19	−0.17	−0.31
PQ-24	**0.36**	−0.25	−0.31	**0.33**	−0.32	−0.38	0.17	−0.24	−0.13	0.19	−0.17	−0.41
PQ-25	**0.33**	−0.32	−0.31	**0.35**	−0.30	−0.45	0.12	−0.08	−0.02	**0.30**	−0.14	−0.34
PQ-26	**0.33**	−0.26	−0.29	**0.32**	−0.25	−0.30	0.05	−0.10	0.10	**0.29**	−0.19	−0.33
PQ-27	**0.34**	−0.22	−0.27	**0.35**	−0.24	−0.29	−0.03	−0.26	0.06	**0.33**	−0.27	−0.27
PQ-28	0.10	−0.27	−0.35	0.14	−0.19	−0.19	−0.01	0.08	0.06	**0.34**	−0.33	−0.25
PQ-29	0.18	−0.37	−0.30	0.25	−0.44	−0.32	0.00	−0.05	−0.15	**0.28**	−0.29	−0.31
TQ-1	0.17	−0.21	−0.26	0.24	−0.26	−0.25	0.17	−0.21	−0.09	**0.30**	−0.27	−0.29
TQ-2	**0.31**	−0.21	−0.10	**0.27**	−0.29	−0.21	0.17	−0.06	−0.28	0.19	−0.17	−0.20
TQ-3	0.19	−0.24	−0.05	0.16	−0.26	−0.18	−0.03	−0.19	−0.15	0.05	−0.04	−0.05
AQ-1	**0.36**	−0.30	−0.20	**0.39**	−0.33	−0.20	−0.10	−0.18	−0.21	**0.38**	−0.33	−0.28
AQ-2	0.23	−0.35	−0.15	0.13	−0.45	−0.23	0.08	−0.54	−0.20	0.13	−0.18	−0.12
AQ-3										0.23	−0.21	−0.34
AQ-4										0.19	−0.11	−0.13
AQ-5										0.23	−0.12	−0.09

and rainfall or runoff, indicating lower values when the northern Atlantic SST is warmer than usual. These signals are rather similar to those displayed in the Andes and in the southern Pacific coast. This could have two explanations. First, the associations between ocean–atmosphere indicators are the same across the three Peruvian drainages. Secondly, as many raingauge stations are located in the Andes and as large parts of the Amazonas basins are in the Andes, the Andean signal dominates the Amazonian hydrology. The relationship between *in situ* rainfall and the SST in the tropical Atlantic confirms the second hypothesis (Fig. 9(d)). Finally, the lack of rainfall in the Amazonas basins when the SST in the northern tropical Atlantic is warm may explain the downward trend in hydrology described in the section above on Runoff and Rainfall Changes and Trends; indeed, a positive trend in the NATL SST is observed between 1970 and 2005 (Fig. 9(b)). These results concur with the results of Espinoza *et al*. (2009a).

CONCLUSION

For the first time, an analysis of rainfall and runoff mean conditions and variability has been conducted, at the basin scale, over the three principal Peruvian drainages: Pacific, Lake Titicaca and Amazonas, for the 1969–2004 period. This work takes advantage of data gathered in 34 basins by SENAMHI as part of the Hydrogeodynamics of the Amazon Basin

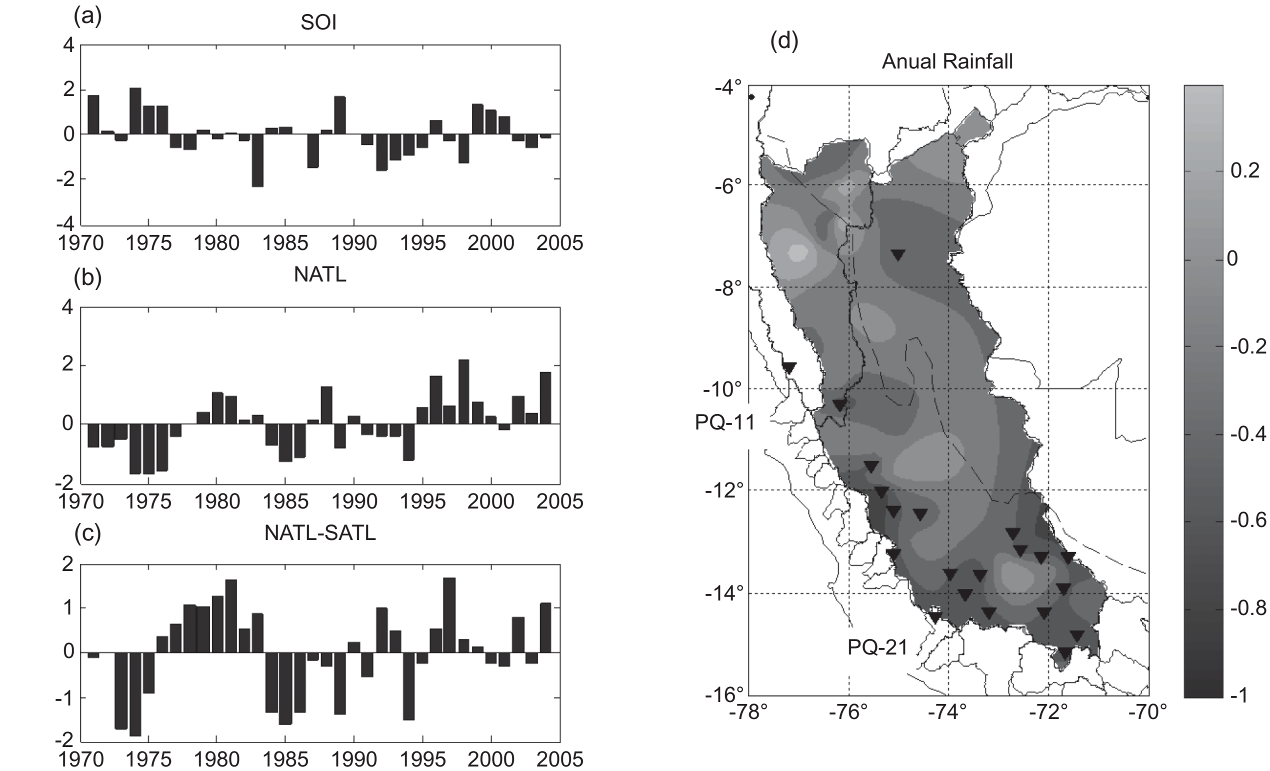

Fig. 9 Standardized annual values (1969–2004 period) of: (a) the Southern Oscillation Index (SOI), (b) the northern tropical Atlantic SST (NATL, 5–20°N, 60–30°W), and (c) the standardized difference between NATL and the southern tropical Atlantic SST (SATL, 0–20°S, 30°W–10°E). (d) Interpolated correlation coefficients between *in situ* rainfall and NATL–SATL in the Ucayali and Huallaga basins. Stations with significant negative correlation values are represented by black downward triangles (95% confidence level). Adapted from Lavado (2010).

(HyBAm) project. It is notable that many of the 29 Pacific basins are influenced by anthropogenic activities, which makes it difficult to understand some results.

In addition to the well-known contrast between the dry coastal basins and the wet eastern lowlands, details are given about *in situ* and per basin rainfall distribution in all regions and about their different altitude–rainfall relationships. Along the coast, a strong south–north rainfall gradient prevails and there is no clear relationship between rainfall and altitude. In the Amazon, a patchwork of rainier and drier regions prevails, together with a rainfall decrease with altitude. Over the Titicaca drainage, annual rainfall is of intermediate values and it diminishes in the highest stations.

Runoff variability is strong in the coastal basins at seasonal and inter-annual time scales, because rainfall variability is high in this part of the country, and because the basins are small and the rivers often intermittent. Rainfall and runoff are more regular in the Andes at the inter-annual time scale, and in the Amazon at intra- and inter-annual time scales.

Trends and change points are observed in the runoff data of Amazonian basins where rainfall and runoff decrease, especially since the mid-1980s and during the low stage season. Over the Titicaca drainage, increases in minimum runoff may be associated with accelerated melting of the glaciers due to climate change. Minimum runoff values in almost all the coastal basins show some change (change points and trends) during the last 35 years. As they are not related to rainfall changes and are not spatially organized, they may be attributed to human activity. Increases in low stage runoff may concur with glacier melting in the Santa basin and with constructions dedicated to sustaining low flow in the rivers that supply water to big cities or intensive farming, but further analysis is necessary to assess this hypothesis.

The analysis of the relationships between hydrology and ocean–atmosphere indicators, such as the Pacific Southern Oscillation Index (SOI) and the sea-surface temperature (SST) over the tropical Atlantic Ocean, gives some indications about the origin of rainfall and runoff variability. A signal that had not been documented before was found between the

Atlantic SST and the hydrology of the southern Andes basins and of the coastal and Amazon drainages fed by the southern Andes. Rainfall and maximum and mean runoff values decrease when the northern tropical Atlantic Ocean is warmer than usual. However, a cooler ocean may displace convection towards the southern tropics and drive strong trade winds and high water vapour fluxes towards the region, enhancing rainfall and runoff. The long-term warming of the northern tropical Atlantic may explain the significant downward trend of runoff observed in the Amazon. As documented before, rainfall and runoff tend to decrease during El Niño events in the tropical Andes and, consequently, in the dependent coastal and Amazonian basins. There is no clear evidence of increased rainfall and runoff on the northern coast during El Niño, except for some extreme events (1982/83 and 1997/98). Further investigations may clarify and complete these first results.

REFERENCES

Aceituno, P., 1988. On the functioning of the Southern Oscillation in the South American sector. Part 1: Surface climate. *Monthly Weather Review*, 116, 505–524.

Aceituno, P. and Montecinos, A., 1993. Circulation anomalies associated with dry and wet periods in the South American Altiplano. Proc. Fourth Int. Conf. On Southern Hemisphere Meteorology, American Meteorological Society.

ACTO, 2005. A proposal for defining the geographical boundaries of Amazonia. *In*: H.D. Eva and O. Huber, eds., *Synthesis of the results from an Expert Consultation Workshop* organized by the European Commission in collaboration with the Amazon Cooperation Treaty Organization – JRC Ispra, 7–8 June 2005.

Brunet-Moret, Y., 1979. Homogénéisation des précipitations. *Cahiers ORSTOM, Série Hydrologie*, 16, 3–4.

Burn, D.H. and Elnur, M.A.H., 2002. Detection of hydrologic trends and variability. *Journal of Hydrology*, 255, 107–122.

Chaffaut, I. *et al*., 1998. Précipitations d'altitude du Nord-Chili, origine des sources de vapeur et données isotopiques. *Bulletin de l'Institut Française d'Etudes Andines*, 27, 367–384.

Deutsch, C.V. and Journel, A.G., 1992. *GSLIB Geostatistical Software Library and User's Guide*. TIC: 224174. New York, New York: Oxford University Press.

Dollfus, O., 1964. Cambios climáticos cuaternarios en los Andes Peruanos. *Boletin de la Sociedad Geografica. Lima*, 83, 65–74

Espinoza, J.C. *et al*., 2006. La variabilité des débits du Rio Amazonas au Pérou. *In*: *Climate variability and change—Hydrological impacts* (Proceedings of the Fifth FRIEND World Conference held at Havana, Cuba, November 2006). Wallingford, UK: IAHS Press, IAHS Publ. 308, 424–429.

Espinoza, J.C. *et al*., 2009a. Contrasting regional discharge evolutions in the Amazon basin (1974–2004. *Journal of Hydrology*, 375, 297–311.

Espinoza, J.C. *et al*., 2007. Hydroclimatic variability in the Andean region of the Amazon basin. Paper read at workshop on Changes to Hydrologic Extremes. IAHS, Perugia (Italy, July 2007).

Espinoza, J.C. *et al*., 2009b. Spatio–temporal rainfall variability in the Amazon Basin countries (Brazil, Peru, Bolivia, Colombia and Ecuador. *International Journal of Climatology*, 29, 1574–1594.

Farr, T.G. *et al*., 2007. The Shuttle radar topography mission. *Review of Geophysics*, 45, RG2004.

Figueroa, S.N. and Nobre, C., 1990. Precipitation distribution over central and western tropical South America. *Climanalise*, 5, 36–44.

Foley, J.A. *et al*., 2002. El Niño-Southern Oscillation and the climate, ecosystems and rivers of Amazonia. *Global Biogeochemical Cycles*, 16 (4), 1132–1152.

Francou, B. and Pizarro, L., 1986. El Niño et la sécheresse dans les hautes Andes centrales: étude d'une possible corrélation. *Les Cahiers d'Outre Mer*, 156, 371–390.

Garreaud, R.D., 1999. Multiscale analysis of the summertime precipitation over the Central Andes. *Monthly Weather Review*, 127 (5), 901–921.

Garreaud, R.D. and Aceituno, P., 2001. Interannual rainfall variability over the South American Altiplano. *Journal of Climate*, 14, 2779–2789.

Garreaud, R., Rutllant, J. and Fuenzalida, H., 2002. Coastal lows in north-central Chile: mean structure and evolution. *Monthly Weather Review*, 130, 75–88.

Garreaud, R., Vuille, M. and Clement, A.C., 2003. The climate of the Altiplano: observed current conditions and mechanisms of past changes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 194, 5–22.

Garreaud, R.D. *et al*., 2009. Present-day South American climate. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 281 (3–4), 180–195.

Gentry, A.H. and Lopez-Parodi, J., 1980. Deforestation and increased flooding of the Upper Amazon. *Science*, 210, 1354–1356.

Guyot, J.-L., 1993. *Hydrogéochimie des fleuves de l'Amazonie bolivienne*. Paris: Editions de l'ORSTOM.

Herreros, J. *et al*., 2009. Environmental records from temperate glacier ice on Nevado Coropuna saddle, southern Peru. *Advances in Geoscience*, 22, 27–34.

Hiez, G., 1977. L'homogénéité des données pluviométriques. *Cahiers ORSTOM, série Hydrologie*, 14, 129–172.

Johnson, A., 1976. The climate of Peru, Bolivia and Ecuador. *In*: *Climates of Central and South America. World survey of climatology* 12, 147–218. New York: Elsevier.

Kane, R.P., 1999. Rainfall extremes in some selected parts of Central and South America: ENSO and other relationships reexamined. *International Journal of Climatology*, 19, 423–455.

Kaser, G. *et al*., 2003. The impact of glaciers on the runoff and the reconstruction of mass balance history from hydrological data in the tropical Cordillera Blanca, Peru. *Journal of Hydrology*, 282, 130–144.

Kendall, M., 1975. *Rank correlation methods*. London: Charles Griffin.

Kundzewicz, Z.W. and Robson, A.J., 2004. Change detection in hydrological records: a review of the methodology: detecting change in hydrological data. *Hydrological Sciences Journal*, 49 (1), 7–19.

Laraque, A. *et al*., 2007. Hydropluviometric regime singularities and the Ecuadorian Amazon basin. *Journal of Hydrometeorology*, 8, 1364–1381.

Lavado, W., 2010. *Modélisation du bilan hydrique à pas de temps mensuel pour l'évaluation de l'impact du changement climatique dans le bassin Amazonien du Pérou*. Thesis (PhD), Université Toulouse 3 Paul Sabatier, Toulouse France.

Mann, H.B., 1945. Non-parametric test against trend. *Econometrica*, 13, 245–259.

Marengo, J.A., 1995. Variations and change in South American streamflow. *Climatic Change*, 31, 99–117.

Marengo, J.A., Tomasella, J. and Uvo, C.R., 1998. Trends in streamflow and rainfall in tropical South America: Amazonia, eastern Brazil, and northwestern Peru. *Journal of Geophysical Research*, 103, 1775–1784.

Marengo, J.A., 2004. Interdecadal variability and trends of rainfall across the Amazon basin. *Theoretical and Applied Climatology*, 78, 79–96.

Mark, B.G., Seltzer, G.O., 2003. Tropical glacier meltwater contribution to stream discharge: a case study in the Cordillera Blanca, Peru. *Journal of Glaciology*, 49, 165, 271–281.

Mark, B.G., McKenzie, J. and Gomez J., 2005. Hydrochemical evaluation of changing glacier meltwater contribution to stream discharge: Callejon de Huaylas, Peru. *Hydrological Sciences Journal*, 50 (6), 975–987.

Mark, B.G. *et al*., 2010. Climate change and tropical Andean glacier recession: evaluation hydrological changes and livelihood vulnerability in the Cordillera Blanca, Peru. *Annals of the Association of American Geographers*, 100, 794–805.

Melice, J. and Roucou, P., 1998. Decadal time scale variability recorded in the Quelccaya summit ice core ^{18}O isotopic ratio series and its relation with the sea surface temperature. *Climate Dynamics*, 14, 117–132.

Nordin, C.F. *et al*., 1982. Deforestation and increased flooding of the Upper Amazon. *Science*, 215, 426–427.

Oliver, M.A. and Webster, R., 1990. Kriging: a method of interpolation for geographical information system. *International Journal of Geographical Information Systems*, 4, 313–332.

Pettitt, A.N., 1979. A non-parametric approach to the change-point problem. *Applied Statistics*, 28, 126–135.

Pouyaud, B. *et al*., 2005. On the future of the water resources from glacier melting in the Cordillera Blanca, Peru. *Hydrological Sciences Journal*, 50 (6), 999–1022.

Poveda, G., 2004. La hidroclimatología de Colombia: una síntesis desde la escala inter-decadal hasta la escala diurna. *Revista de la Academia Colombiana de Ciencias*, 28, 201–222.

Pulwarty, R.S., Barry, R.G. and Riehl, H., 1992. Annual and seasonal patterns of rainfall variability over Venezuela. *Erdkunde*, 46, 273–289.

Richey, J.E., Nobre, C. and Deser, C., 1989. Amazon River discharge and climate variability: 1903 to 1985. *Science*, 246, 101–103.

Rigsby, C.A., Baker, P.A. and Aldenderfer, M.S., 2003. Fluvial history of the Rio Ilave valley, Peru, and its relationship to climate and human history. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 3061, 1–21.

Robson, A. *et al*., 2000. Statistical methods for testing for change. Chapter 5 i*n*: Z.W. Kundzewicz and A. Robson, eds., *Detecting trend and other changes in hydrological data*. Geneva: World Meteorological Organization, WMO/TD 1013.

Rocha, H.R.d., Nobre, C.A. and Barros, M.C., 1989. Variabilidade natural de longo prazo no ciclo hidrologico da Amazonia. *Climanálise*, 4, 36–42.

Roche, M. *et al*., 1990. Hétérogénéité des précipitations sur la cordillère des Andes boliviennes. *In*: H. Land and A. Musy, eds., *Hydrology in mountainous regions I – Hydrological measurements, the water cycle*. Wallingford, UK: IAHS Press, IAHS Publ. 193, 381–388.

Rome-Gaspaldy, S. and Ronchail, J., 1998. La pluviométrie au Pérou pendant les phases ENSO et LNSO. *Bulletin de l'Institut Française d'Etudes Andines*, 27, 675–685.

Romero, C.C., Baigorria, G.A. and Stroosnijder, L., 2007. Changes of erosive rainfall for El Niño and La Niña years in the northern Andean highlands of Peru. *Climatic Change*, 85, 343–356.

Ronchail, J. *et al*., 2002. Interannual rainfall variability in the Amazon basin and sea-surface temperatures in the equatorial Pacific and the tropical Atlantic Oceans. *International Journal of Climatology*, 22, 1663–1686.

Ronchail, J. and Gallaire, R., 2006. Enso and rainfall along the Zongo valley (Bolivia) from the Altiplano to the Amazon basin. *International Journal of Climatology*, 26, 1223–1236.

Ropelewski, C.F. and Halpert, M.S., 1987. Global and regional scale precipitations patterns associated with El Nino-Southern Oscillation. *Monthly Weather Review*, 115, 1606–1626.

Ruiz, R.R., Torres, H.G. and Aguirre, M.N., 2008. Delimitación y codificación de unidades hidrográficas del Perú. Lima, Peru: Autoridad Nacional del Agua-Ministerio de Agricultura.

Rutllant, J., Fuenzalida, H. and Aceituno, P., 2003. Climate dynamics along the arid northern coast of Chile: the 1997–1998. Dinámica del clima de la Región de Antofagasta (DICLIMA) experiment. *Journal of Geophysical Research*, 108 (D17), 4538–4552.

Sicart, J.E., 2002. *Contribution à l'étude des flux d'énergie, du bilan de masse et du débit de fonte d'un glacier tropical: Le Zongo, Bolivie.* Thèse de doctorat, Univ. Paris 6, France.

Tapley, T.D. and Waylen, P.R., 1989. A mixture model of annual precipitation in Peru. *The Professional Geographer*, 41, 62–71.

Tapley, T.D.J. and Waylen, P.R., 1990. Spatial variability of annual precipitation and ENSO events in western Peru. *Hydrological Sciences Journal*, 35, 429–445.

UNESCO, 2006. Balance hídrico superficial del Perú a nivel multianual. Montevideo: Documentos Técnicos del PHI-LAC, no. 1.

Vauchel, P., 2005. Hydraccess: Logiciel de gestion et traitement de données hydro météorologiques, version 2.1.4. Downloadable at http://www.mpl.ird.fr/hybam.01/01/2011

Vizy, E.K. and Cook, K.H., 2007. Relationship between Amazon and high Andes rainfall. *Journal of Geophysical Research—Atmospheres*, 112 (D7) 14 pp. doi:10.1029/2006JD007980

Vuille, M. *et al*., 1998. Atmospheric circulation anomalies associated with 1996/1997 summer precipitation events on Sajama ice cap, Bolivia. *Journal of Geophysical Research—Atmospheres*, 103 (D10), 11191–11204.

Vuille, M., Bradley, R.S. and Keimig, F., 2000. Interannual climate variability in the Central Andes and its relation to tropical Pacific and Atlantic forcing. *Journal of Geophysical Research—Atmospheres* 105, 12447–12460.

Vuille, M. *et al*., 2008a. Climate change and tropical Andean glaciers: Past, present and future. *Earth-Science Reviews*, 89, 79–96.

Vuille, M., Kaser, G. and Juen, I., 2008b. Glacier mass balance variability in the Cordillera Blanca, Peru and its relationship with climate and the large-scale circulation. *Global and Planetary Change*, 62, 14–28.

Wagnon, P. *et al*., 1999. Annual cycle of energy balance of Zongo glacier, Cordillera Real, Bolivia. *Journal of Geophysical Research*, 104 (D4), 3907–3923.

Wagnon, P. *et al*., 2001. Anomalous heat and mass budget of Glaciar Zongo, Bolivia, during the 1997–98 El Niño year. *Journal of Glaciology*, 47 (156), 21–28.

Waylen, P. and Poveda, G., 2002. El Niño-Southern Oscillation and aspects of western South American hydro-climatology. *Hydrological Processes*, 16 (6), 1247–1260.

Waylen, P.R. and Caviedes, C.N., 1986. El Niño and annual floods on the north Peruvian littoral. *Journal of Hydrology*, 89 (1–2), 141–156.

Yoon, J.H. and Zeng, N., 2009. An Atlantic influence on Amazon rainfall. *Climate Dynamics*, 34 (2–3), 249–264.

Zhang, X.B. *et al*., 2001. Trends in Canadian streamflow. *Water Resources Research*, 37 (4), 987–998.

Zhou, J. and Lau, K-M., 1998. Does a monsoon climate exist over South America? *Journal of Climate*, 11, 1020–1040.