ELSEVIER

Journal of Hydrology 165 (1995) 221–234

Journal of Hydrology

[1]

Tropical climate and glacier hydrology: a case study in Bolivia

P. Ribstein[a,*], E. Tiriau[a], B. Francou[a], R. Saravia[b]

[a]*Départment des Eaux Continentales, l'institut français de recherche scientifique pour le développement en coopération, ORSTOM, CP 9214, La Paz, Bolivia*

[b]*Compañia Boliviana de Energía Eléctrica S.A., COBEE S.A., CP 353, La Paz, Bolivia*

Received 7 December 1993; revision accepted 22 June 1994

Abstract

Runoff from intertropical glaciers is highly variable, indicating that they are greatly affected by climatic changes peculiar to tropical climates. The 3 km^2 basin presented in this case study lies in the Cordillera Real of Bolivia and is 77% covered by glacier ice, ranging in elevation from 6000 to 4830 m a.s.l. A comparison of 2 years of study demonstrates the peculiar feature of intertropical glaciers: that accumulation and melting periods coincide during the rainy season. During the first hydrological year (1991–1992), runoff was 1793 mm for an average precipitation on the glacier of approximately 916 mm. During the second year (1992–1993), runoff was 1080 mm for a precipitation of 1060 mm. Solar radiation and daily mean duration with positive temperature on the ablation zone are the parameters best explaining variation in monthly runoff. Gauge readings taken downstream enable discharge from the glacier to be established over a period of nearly 20 years. The most prominent events coincide with significantly negative values of the Southern Oscillation Index, often linked to El Niño-Southern Oscillation (ENSO) phenomena. In conclusion, results show that these intertropical glaciers are receding rapidly, as precipitation does not compensate for loss from melting.

---

1. Introduction

In many parts of the world, glaciers contribute significant quantities of water to surrounding lowlands. At low latitudes, they compensate for strongly seasonal rainfall distribution. The influence of glaciers on the Amazon water system has been discussed (Bourges et al., 1990), but never quantified owing to lack of reliable data. Tropical glaciers are also an interesting research topic in terms of their response

---

* Corresponding author.

SSDI 0022-1694(94)02572-X

to atmospheric forcing. Nevertheless, little investigation has been carried out on glaciers in the intertropical zone (Young, 1985).

Glacier inventories have recently been published for Peru and Bolivia (Hidrandina, 1988; Jordan, 1991). Some studies have been carried out, concentrating either on climatic aspects (Hastenrath, 1978; Thompson et al., 1984) or glaciological aspects (Kaser et al., 1990), but practically no studies exist in the field of hydrology. Measurement of glacier runoff has been of prime importance in a study carried out since 1991 in Cordillera Real of Bolivia (Francou et al., 1994). The main purpose of this research is to quantify current retreat of Andean glaciers and to investigate the underlying climatic parameters. In order to analyze the relationship between climatic fluctuations and glacial hydrology, it is necessary to have accurate information on water volumes lost from glaciers through runoff.

2. The investigation area

The glacier in this case study, Zongo Glacier, forms part of the Huayna Potosí massif (16°15′S, 68°10′W) in the Cordillera Real, Bolivia, approximately 30 km north of La Paz. This glacier with a surface area of 2.1 km^2 is part of a 3 km^2 basin above the main hydrometric station (Fig. 1). The surface not covered by the main glacier comprises two lateral moraines, outcrops of granodiorite and small glacierized areas (supplementary glaciers of 0.2 km^2) connected hydrologically but not glaciologically to the main glacier. The basin is 77% covered by glaciers, with altitudes ranging from 6000 m to 4830 m a.s.l. The head of the glacier faces south while the lower part faces east.

The climate of the region is determined by seasonal oscillation in the intertropical convergence zone (ITCZ). During austral winter, the ITCZ is north of Bolivia and tropical anticyclones produce a somewhat cold, dry season. During austral summer, from December to March, the ITCZ proceeds to its most southerly position. This is the wet, as well as the warm season, coinciding with the eastern intertropical flux that brings water vapour from the Atlantic (Montes de Oca, 1982; Roche et al., 1990). In the study zone, water-vapor transport is from the north, with air masses drying as they rise up the Zongo valley, part of the Amazon basin. However, significant precipitation is not uncommon in July and August with cold fronts, observed during both years of this study.

3. Instrumentation and measurements

Equipment was installed in July 1991 (glaciological stakes, hydrometric station, rain gauges, thermograph). In early 1993, a recording rain gauge, additional thermographs and a pyranometer for short wave radiation records were added (Fig. 1).

Fifteen ablation stakes were distributed over the ablation zone, from 5200 m down to 4900 m a.s.l. Three stakes were placed in the accumulation zone at 5600 m a.s.l. In addition, soundings were made for snow density and depth.

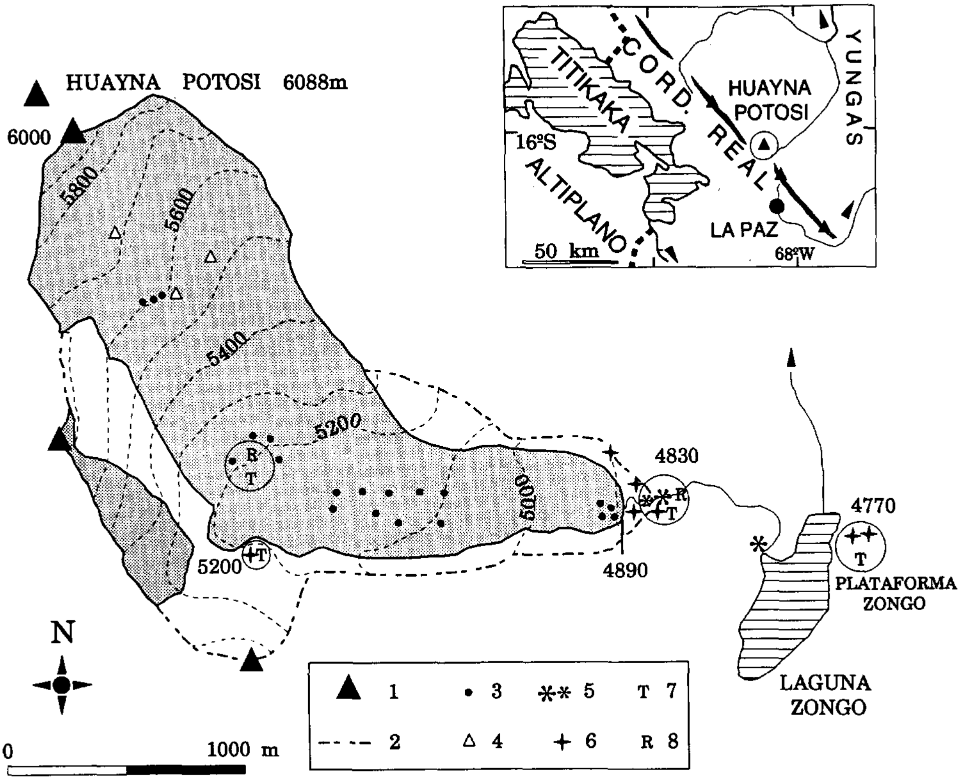

Fig. 1. Sketch map of Huayna Potosí and Zongo Glacier (Bolivia) with the system of survey in 1993. Shaded areas represent glaciers. 1, principal peaks; 2, limits of the basin; 3, glaciological stakes; 4, soundings from pits and crevasses; 5, hydrometric stations; 6, precipitation gauges; 7, thermographs; 8, pyranometers.

The rainfall pattern was initially determined from a daily rain gauge in operation since 1970 at the Plataforma Zongo, 1000 m from the glacier tongue, at an altitude of 4770 m. Furthermore, around the ablation zone, five storage precipitation gauges with 2000 cm^2 orifices were read monthly, evaporation being inhibited by a layer of oil. The measured precipitation was compared with several readings of snow depth taken on the glacier. Because of considerable direct sunlight and temperatures frequently above 0°C during the rainy season, the lower part of the basin receives more rain than snow. Furthermore, solid precipitation on the rock-covered borders and moraines melts very quickly.

The main station installed for measuring temperature is also situated at 4770 m on the Plataforma Zongo and has been equipped with a thermograph since July 1991. A comprehensive set of temperature records since 1945 is available for the El Alto station (altitude 4071 m, 30 km distance from the glacier). Changes in location and instrumentation, however, compel the reference period to be limited to 1970–1993. Temperature has also been recorded at the hydrometric station and also at an altitude of around 5200 m since early 1993.

The hydrometric station is at an altitude of 4830 m, 60 m lower and 150 m downstream from the glacier tongue. This station, set up in 1991, comprises a water level recorder and a triangular weir. Downstream from the station the river enters Lake Zongo, which supplies a nearby hydroelectric plant. Since 1973 two daily readings have been taken at a staff gauge on a rectangular weir, between the hydrometric station at 4830 m and Lake Zongo. Several discharge measurements, together with comparisons of readings at the staff gauge and those from the hydrometric station, enable discharges from glacier melting to be established from 1973 onwards.

The high temperatures common to these latitudes lead to very few problems related to freezing, and easy year-round access to the glaciers of the Cordillera Real facilitates frequent supervision of the instruments, not only reducing the number of gaps in the records but also increasing record quality.

4. Results and discussion

4.1. Climatic variation

Tropical climate varies highly from one year to another. Mean annual precipitation at the Plataforma Zongo from 1970 to 1993 was 885.7 mm. During the hydrological year 1991–1992 it was 686 mm, with 919.5 mm in 1992–1993. Hence, the 1991–1992 period was below average (77% of the mean), while the second period was closer to the mean. The below average precipitation in the first year is linked to a very short rainy season. For 1991–1992, only four months have greater than 50 mm rainfall

Table 1
Monthly and yearly values of precipitation and temperature at Zongo station and El Alto station

Month	*P* 91–92 Zongo (mm)	*P* 92–93 Zongo (mm)	*Pm* 70–93 Zongo (mm)	*T* 91–92 Zongo (°C)	*T* 92–93 Zongo (°C)	*T* 91–92 El Alto (°C)	*T* 92–93 El Alto (°C)	*Tm* 70–93 El Alto (°C)
Sept.	25.2	21.0	40.2	0.9	0.3	5.8	6.3	6.2
Oct.	42.4	59.8	54.8	2.6	0.5	7.6	7.5	7.7
Nov.	94.3	90.4	76.3	2.3	1.4	8.0	8.1	8.4
Dec.	83.9	123.1	118.0	2.3	−0.1	8.6	8.5	8.1
Jan.	171.5	249.2	198.0	1.3	0.5	7.6	7.2	7.5
Feb.	134.4	100.2	152.0	1.1	1.5	7.8	7.9	7.5
March	32.6	145.8	135.8	2.4	0.7	7.8	7.2	7.5
April	14.0	63.0	55.2	2.6	2.0	7.6	7.3	7.0
May	0.9	13.4	12.3	3.1	2.3	7.1	6.3	5.8
June	18.5	3.5	12.1	0.9	2.6	5.0	4.5	4.1
July	21.9	4.5	7.3	0.5	0.7	3.8	4.2	3.8
Aug.	46.4	45.6	23.7	−0.8	0.1	4.0	4.7	5.0
Year	686.0	919.5	885.7	1.6	1.0	6.7	6.6	6.5

P, precipitation; *Pm*, mean precipitation (1970–1993 period); *T*, temperature; *Tm*, mean temperature (1970–1993 period).

(from November to February), usually there are seven such months according to data compiled from 1970–1993.

The 1991–1992 year was warmer than the second, 1.6°C instead of 1.0°C (Table 1). At El Alto station, mean annual temperature for each year was 6.7°C and 6.6°C for 1991–1992 and 1992–1993, respectively, close to the long-term annual mean of 6.5°C. However, Fig. 2 shows that from December 1991 to June 1992, monthly temperatures were appreciably above average. The period under observation therefore covers a dry, rather warm year as well as one with close to average values.

Annual rainfall calculation on the basin requires firstly a study of the relationship between rain and altitude. Comparison of multiyear data from the Zongo station (4770 m a.s.l.) and at Botijlaca (3490 m a.s.l., 12 km from the Zongo station) in the same valley, shows a slight negative gradient; nevertheless, total rainfall over the observed period shows that there is a difference of less than 4% between the two stations, monthly values being very close. The various soundings carried out at altitudes ranging from 5500 to 5800 m and monthly readings taken from five storage precipitation gauges (ranging from 4800 to 5200 m) prove that there is no marked gradient between precipitation in relation to altitude on the Zongo Glacier. On the

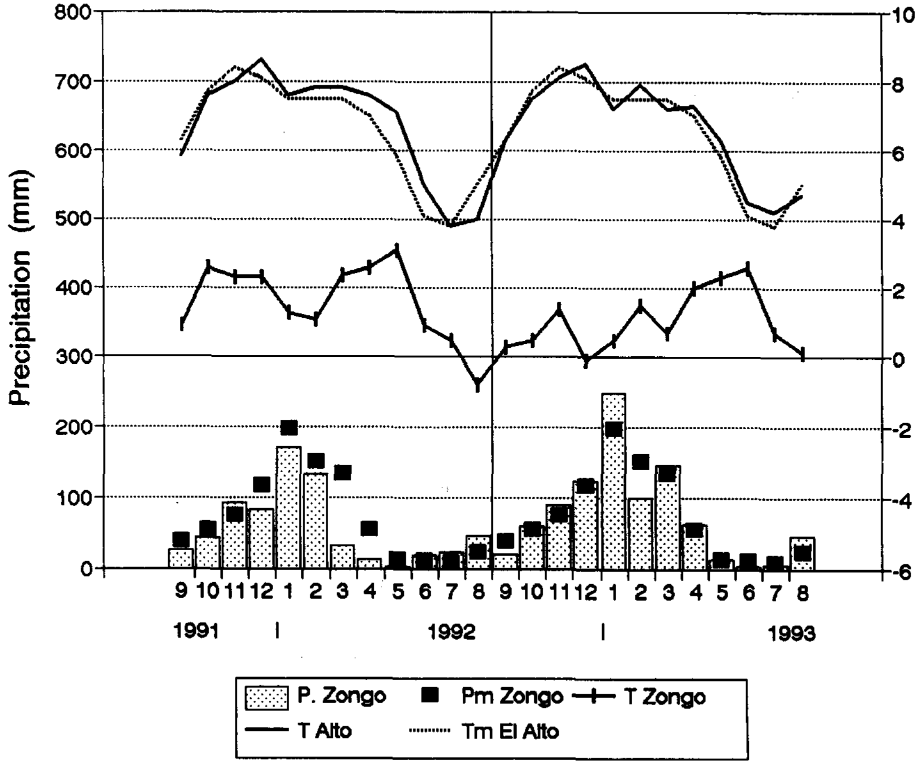

Fig. 2. Monthly temperature and precipitation at Zongo station. Temperatures are compared with El Alto station during the observed period and with El Alto mean monthly values (1970–1993 period). Precipitation is compared with Zongo mean monthly values (1970–1993 period).

contrary, during the first year, annual rainfall at the Plataforma Zongo was 25% below the mean registered in the storage precipitation gauges and during the second year it was 13%. The difference may be explained by gauge catch deficiency for solid precipitation due to wind; this deficiency is larger for the Zongo rain gauge of 314 cm^2 area than for storage precipitation gauge of 2000 cm^2 area.

There is up to 20% variation in annual rainfall from one storage precipitation gauge to another. The location of storage precipitation gauges have being selected in order to represent situations with different characteristics, assuming that each gauge was representative of an equally large area. For an evaluation of the hydrological regime during the 2 years covering this study, it has been necessary to take, as precipitation index for the glacier, the mean of the storage precipitation gauges: 916 mm for 1991–1992, 1060 mm for 1992–1993. Therefore, it may be inferred that the temporal variation in precipitation on the glacier is well represented by the rain gauge on the Plataforma Zongo. However, mean precipitation on the basin is about 20% greater than that recorded at Zongo station. Spatial precipitation estimates are not easy to compute, especially in the case of mountainous regions with snowfall. Thus, uncertainty in the mean precipitation is estimated to be less than 20%, a normal accuracy for gauged precipitation in mountainous regions (Kattelmann and Elder, 1991).

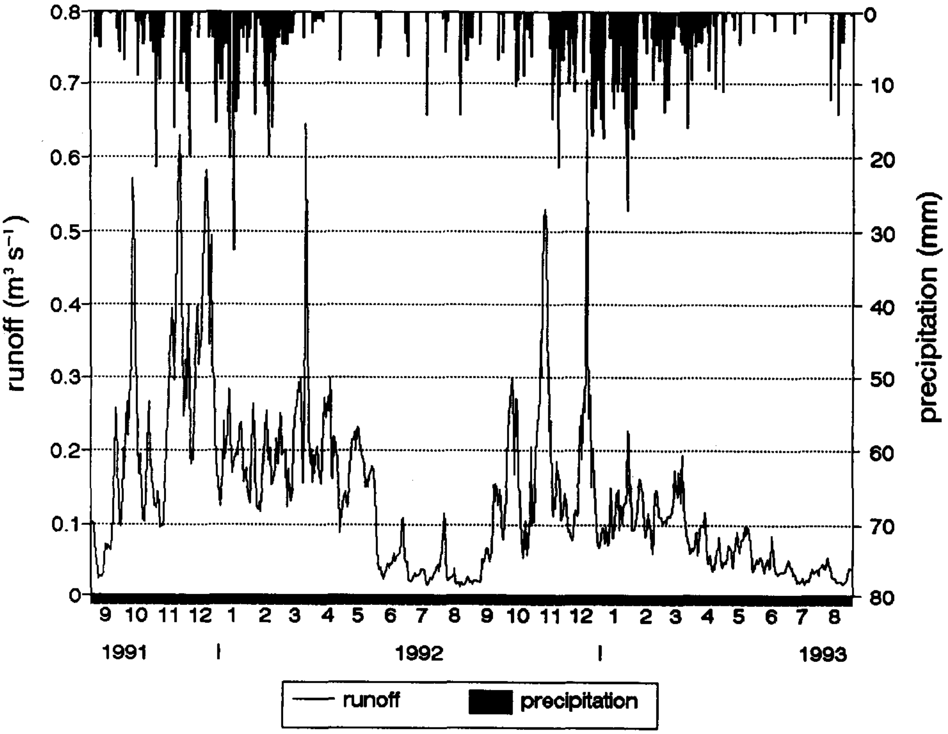

Fig. 3. Daily precipitation at Zongo station and daily streamflow at hydrometric station at 4830 m a.s.l. during 1991–1993.

Precipitation is very seasonal with 82% in 1991–1992 and 84% in 1992–1993 of annual precipitation falling from October to March. Temperature characteristics are not notably seasonal, particularly at high altitude: at Plataforma Zongo the coldest month of the second year was December, during the supposedly warm season! At Zongo (4770 m a.s.l.) from 1991–1993 there is a 3.9°C difference between the warmest and the coldest month, yet there is an average diurnal range of 7.9°C, typical of tropical high altitudes (Hastenrath, 1991).

4.2. *Hydrological regime at the glacier outlet*

Comparison of daily rainfall and runoff (Fig. 3) reveals the most significant hydrological characteristic of intertropical glaciers: the accumulation and ablation periods are simultaneous. These glaciers behave similarly to 'the summer-accumulation type', of the Himalayas and Tibetan Plateau (Ageta and Kadota, 1992). Annual values (Table 2) show wide runoff variability from year to year, and the highly significant balance deficit observed during the first year: 1793 mm runoff for a precipitation of 916 mm. The second year is more evenly balanced, with 1080 mm runoff for a precipitation of around 1060 mm.

Runoff is less seasonal than rainfall (Table 2). During the 2 years of the present study, 72% and 76%, respectively, of total annual runoff occurred during the 6 months from October to March. The highest monthly discharges were in November and December which do not coincide with the 2 months with the heaviest precipita-

Table 2
Monthly and yearly values of incident solar radiation at Huayna Potosi, mean daily duration with temperature above 3°C at Zongo station, runoff depth for 1991–1993 and mean values for 1973–1993

Month	H_o ($\mathrm{W\,m^{-2}}$)	DT3 91–92 ($\mathrm{h\,day^{-1}}$)	DT3 92–93 ($\mathrm{h\,day^{-1}}$)	*R* 91–92 (mm)	*R* 92–93 (mm)	*Rm* 73–93 (mm)	*R*std 73–93 (mm)
Sept.	404	4.9	5.1	76	59	71	42
Oct.	439	7.4	4.7	205	136	142	53
Nov.	456	8.3	5.9	237	202	211	91
Dec.	460	8.8	3.4	305	180	213	57
Jan.	458	5.2	3.5	171	102	176	70
Feb.	448	4.4	6.1	155	92	163	63
March	421	8.3	4.0	217	104	165	96
April	377	9.7	6.4	168	58	118	59
May	334	11.0	8.1	160	58	84	31
June	312	5.9	8.5	46	37	49	24
July	321	6.0	6.1	25	26	36	15
Aug.	358	3.7	5.2	29	28	44	22
Year	399	7.0	5.6	1793	1080	1472	383

The runoff depth is related to the basin area of $3.0\,\mathrm{km^2}$.
H_o, solar radiation; DT3, mean daily duration; *R*, runoff depth; *Rm*, mean runoff depth (1973–1993 period); *R*std, standard deviation of runoff depth (1973–1993 period).

tion, January and February or March. This emphasizes the regulating nature of glaciers compared with basins with entirely pluvial runoff.

High discharges are not associated with significant precipitation (Fig. 3). Monthly discharge is only weakly correlated to precipitation (correlation coefficient $r = 0.3$, $n = 24$).

Six episodes with discharges above 0.5 $m^3 s^{-1}$ (in October 1991, November 1991, December 1991, March 1992, November 1992 and December 1992) were each preceded by at least a 10 day dry period (at the most 1 day of precipitation) with maximum temperatures almost always above 5°C on the Plataforma Zongo (see Fig. 4, the event from November 1991). An essential prerequisite to high runoff is an accumulation of energy. The mean temperature gradient on the basin is 0.74°C per 100 m, and the glacier equilibrium line altitude (ELA) is around 5200 m a.s.l.

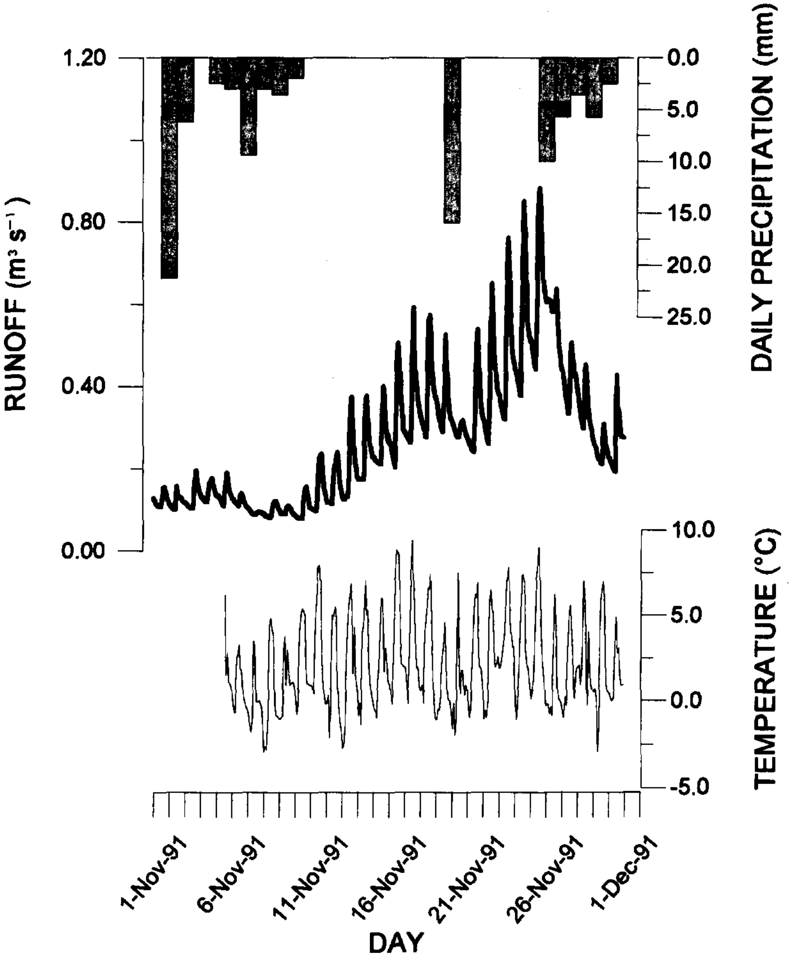

Fig. 4. Flood of November 1991, compared with temperature and precipitation at Plataforma Zongo.

(Francou et al., 1994). Consequently, temperatures above 3°C at the Zongo station (4770 m a.s.l.) correspond to temperatures above 0°C on the ablation zone of the glacier, when melting must be occurring over the entire ablation zone. Discharge is highly correlated to the mean daily duration with temperature above 3°C (DT3) at the Zongo station. This duration DT3 also takes into account the variation in albedo.

There is less ablation when the albedo is high as a result of fresh snowfalls and also when clouds reduce solar radiation reaching the glacier (with low temperatures). Hence, albedo and cloud cover should lead to higher runoff in winter, however the highest discharges occur from October to March. The seasonal nature of runoff is explained primarily by incident solar radiation. For latitudes corresponding to the Zongo Glacier, monthly radiation calculated using equations from Paltridge and Platt (1976), are presented with DT3 and runoff in Table 2. The lowest discharges occur during winter months (July and August), when incident solar radiation is low. The six floods mentioned above are dispersed around the solstice of 21 December.

Based on a stepwise multiple linear regression applied to possible independent variables (precipitation, number of days with precipitation, maximum temperature, mean temperature, average diurnal range, mean daily duration with temperature above different values, ...), monthly runoff R (in mm) is largely explained by two variables: incident solar radiation H_0 (in W m^{-2}); and mean daily duration DT3 (in hours) with temperature above 3°C. The linear model thus obtained is expressed as:

$$R = 1.28H_0 + 23.58\mathrm{DT3} - 538.1 \quad (r = 0.92, n = 24)$$

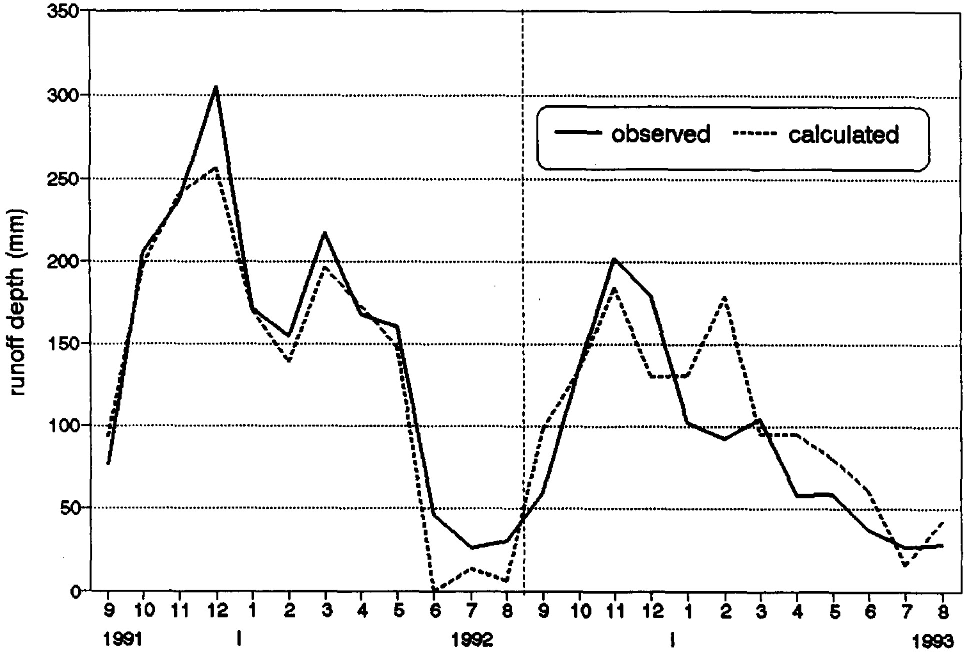

Fig. 5. Observed and calculated runoff from linear regression with solar radiation and mean daily duration with temperature above 3°C at Zongo station.

Monthly results of this regression are represented on Fig. 5. The 1 month time interval does not take into account the considerable daily variations but it does allow for the lag-time between daily meteorological parameters and runoff. The above equation is close to a model of the temperature-index type with seasonally varied melt factor, as expounded by Braun and Aellen (1990). It clearly reflects the importance of solar radiation resulting from the glacier being close to the Equator and at high altitude.

4.3. Climatic fluctuations and glacier runoff since 1973

Daily discharge calculated on the basis of two daily readings downstream from the glacier is highly correlated to discharge at the main hydrometric station from 1991 to 1993 ($r = 0.95$, $n = 600$). This correlation makes it possible to establish monthly discharge from the glacier since 1973 based on established daily discharge. Due to missing daily readings, 14 monthly discharges (out of 240 since 1973) have not been established by means of this correlation. Where it was impossible to establish a complete year because of these missing data, a correlation was applied with the mean monthly temperatures of the El Alto station ($r = 0.85$, $n = 226$). Fig. 6 shows calculated runoff and temperature at the El Alto station: monthly values and 12 month moving average to filter out annual cycles and to reveal the similar behavior of temperature and runoff. Table 2 gives the interannual means thus obtained and shows the first year of the study to present excess runoff. Despite temperature and precipitation close to mean values, the runoff of the second year is lower than the multiyear mean runoff owing to daily rainfall distribution. On average, the greatest runoff occurs in November and December. In certain years, monthly values show two runoff peaks, as in 1991–1992.

It is possible to compare variation in runoff from this intertropical glacier, with that from Northern Hemisphere glaciers. Fountain and Tangborn (1985) on glaciers in the United States and Chen and Ohmura (1990) on alpine glaciers, have analyzed the relationship between the proportion of glacier cover and the coefficient of variation of annual runoff (*Cv*, standard deviation divided by mean). For a 77% covered glacier such as the Zongo, the two studies offer *Cv* values below 0.2, while the coefficient of variation estimated for the Zongo Glacier is 0.26. This runoff variation, greater than the variation of annual rainfall (coefficient of variation 0.17 at El Alto station for 1973–1993), is due mainly to the variability in the duration of rainy season. The greatest standard deviation of monthly runoff is in November and March (Table 2), limiting the wettest months of December, January and February. If the rainy season starts late, glacier runoff is strong in November, whereas if it ends early, runoff is strong in March.

To understand the interannual performance, it is essential to consider the ENSO phenomenon (El Niño-Southern Oscillation). This phenomenon is characterized by significantly negative values of the Southern Oscillation Index (SOI, difference in pressure between Tahiti and Darwin in standardized values). Some studies have shown that ENSO events are associated with drought on the Altiplano (Thompson et al., 1984; Francou and Pizarro, 1985; Tapley and Waylen, 1990), with conditions favorable for glacier melting, and unfavorable for runoff in glacier-free areas. A first

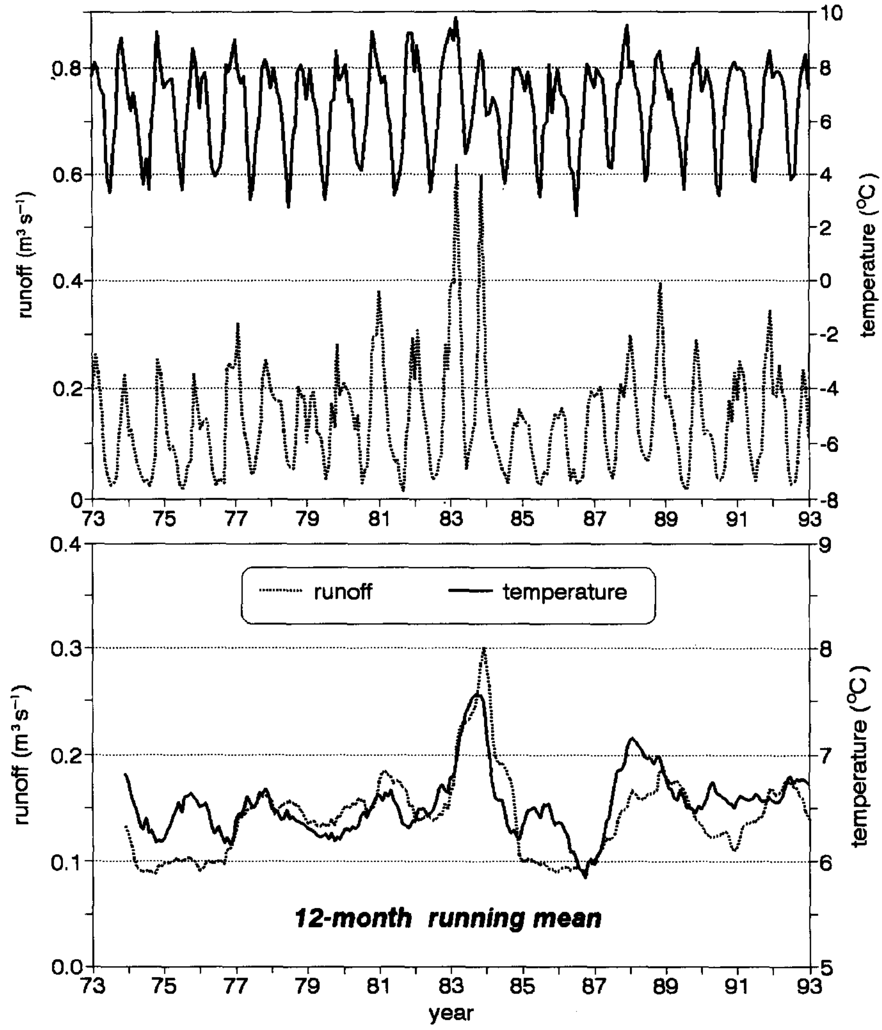

Fig. 6. Monthly runoff (estimated) and temperature at El Alto station, during 1973–1993. The 12 month running mean filters out seasonal variability (figure down).

analysis of the relationship between SOI and runoff from the Zongo Glacier is presented below (further work is in preparation).

Fig. 7 presents a 12 month moving average (to filter out seasonal variability) of SOI and runoff. During the period referred to in this study, four events are associated with strong negative SOI: 1977/1978, 1982/1983, 1986/1987 and 1991/1992. Above average runoff is associated with each of these events. The 1982/1983 phenomenon was one of the most significant ENSO events of the century, producing two periods of high glacier runoff, from January to May 1983 and from October to December 1983, with runoff remaining above average between these two periods. Each significantly negative SOI event is associated with positive temperature deviation at El Alto

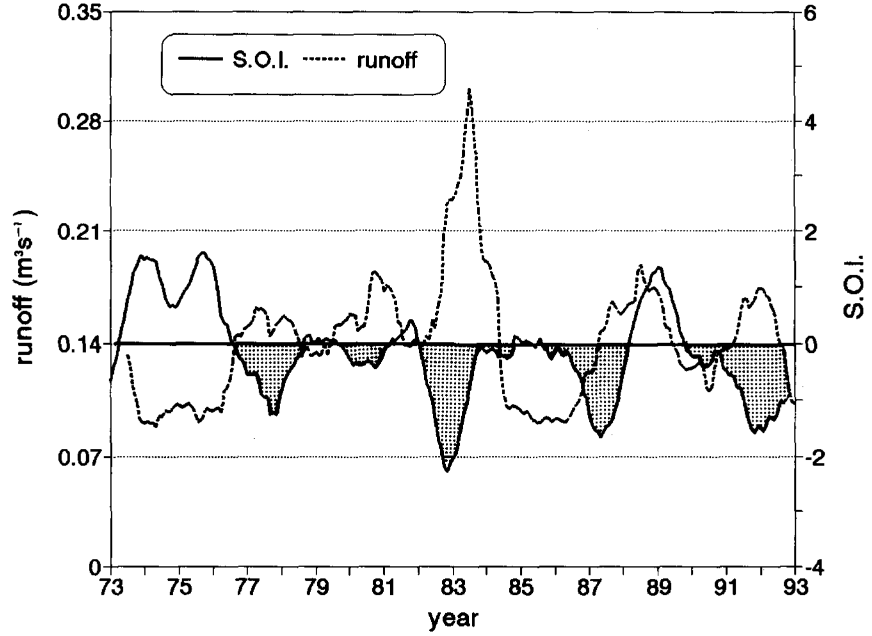

Fig. 7. The 12 month running mean of runoff and SOI. Shaded areas correspond to significantly negative SOI.

station. However, certain positive temperature deviations are not associated with strong negative SOI, (as, for example, in 1980 and 1981), yet result in even higher runoff than any accompanied by an ENSO event, as is the case in 1977/1978. Correlation between monthly runoff and SOI is weak ($r = 0.48$, $n = 240$). The best correlation ($r = 0.61$, $n = 234$) is with 5 month lagged discharge. It is this same 5 month delay that produces the best correlation between SOI and monthly El Alto temperatures ($r = 0.60$, $n = 234$).

Remembering the large uncertainty in the average precipitation on the basin, a mean precipitation index, 20% higher than precipitation at Plataforma Zongo, is 1062 mm for a runoff of 1472 mm (410 mm deficit). Eleven of the 17 years studied show extremely negative balance. Evaporation and sublimation seem to be low, compared with melting runoff (Francou et al., 1994). However, if they were taken into account, this hydrological balance would be even more negative! Outputs from the system being greater than inputs, the glacier reacts in the form of significant retreat at the terminus. Between August 1991 and August 1992, the terminus retreat was 10–20 m.

5. Conclusion

ENSO phenomena are associated with warm, dry periods in the tropical Andes, but produce increased runoff from highly glacierized basins such as Zongo, even though there is a decrease in runoff associated with rainfall. The 2 years observed in this study illustrate the variation in the hydrology of Central Andean glaciers. The significant runoff observed in 1991–1992 (ENSO event) is caused by considerable discharges both at the beginning and the end of the rainy season (from October to December, from March to May). The second hydrological cycle studied 1992–1993 offers climatic characteristics close to mean values, yet produces a somewhat deficient runoff compared with the series of runoff established since 1973. Occurrence of accumulation and melt in the same season accounts for the marked hydrological variation observed since a decrease in precipitation is related to a decrease in cloud cover, and thus results in a period of intense solar radiation, leading each time to a remarkable increase in discharge. The unbalanced hydrology of these glaciers and their retreat are not presented as a normal and continuous phenomenon, but rather as a series of discrete events. This assessment is true at an annual level with atmospheric forcing like the ENSO events, as well as at a daily level with floods during dry periods occurring in the rainy season.

Acknowledgments

We are grateful for the assistance received from UMSA (Universidad Mayor de San Andrés) and SENAMHI (Servicio Nacional de Meteorología e Hidrología) in La Paz. The authors wish to thank J. Bourges, R. Hoorelbeke and R. Vargas for their invaluable assistance during the first year of research. They also wish to mention the personnel at COBEE, especially F. Quispe, thanks to whom monthly recordings were guaranteed from the very start of the study. Data from the El Alto station were supplied by AASANA (Administración de Aeropuertos y Servicios Auxiliares a la Navegación Aérea). Data of the Southern Oscillation Index were made available by the National Oceanic and Atmospheric Administration (US Department of Commerce). This paper benefited from the detailed and helpful comments of three anonymous reviewers.

References

Ageta, Y. and Kadota, T., 1992. Predictions of changes of glacier mass balance in the Nepal Himalaya and Tibetan Plateau: a case study of air temperature increase for three glaciers. Ann. Glaciol., 16: 89–94.

Bourges, J., Guyot, J.L., Carrasco, M., Barragan, M.C. and Cortes, J., 1990. Evolution spatio-temporelle des débits et des matières particulaires sur un bassin des Andes boliviennes: le Rio Beni. In: H. Lang and A. Musy (Editors), Hydrology in Mountainous Regions I. Hydrological Measurements; the Water Cycle. Publ. No. 193, International Association of Hydrological Sciences, Wallingford, pp. 351–356.

Braun, L.N. and Aellen, M., 1990. Modelling discharge of glacierized basins assisted by direct measurements of glacier mass balance. In: H. Lang and A. Musy (Editors), Hydrology in Mountainous Regions I. Hydrological Measurements; the Water Cycle. Publ. No. 193, International Association of Hydrological Sciences, Wallingford, pp. 99–106.

Chen, J. and Ohmura A., 1990. On the influence of Alpine glaciers on runoff. In: H. Lang and A. Musy (Editors), Hydrology in Mountainous Regions I. Hydrological Measurements; the Water Cycle. Publ. No. 193, International Association of Hydrological Sciences, Wallingford, pp. 117–125.

Fountain, A.G. and Tangborn, W.V., 1985. The effect of glaciers on streamflow variations. Water Resour. Res., 21(4): 579–586.

Francou, B. and Pizarro, L., 1985. El Niño y la sequía en los Altos Andes Centrales (Perú y Bolivia). Bull. de l'institut français d'études andines, 14(1–2): 1–18.

Francou, B., Ribstein, P., Saravia, R. and Tiriau, E., 1994. Monthly balance and water discharge on an intertropical glacier: the Zongo Glacier, Cordillera Real, Bolivia, 16°S. J. Glaciol., in press.

Hastenrath, S., 1978. Heat-budget measurements on the Quelccaya Ice Cap, Peruvian Andes. J. Glaciol., 20(82): 85–97.

Hastenrath, S., 1991. Climate Dynamics of the Tropics. Atmospheric Sciences Library, Kluwer Academic, Dordrecht.

Hidrandina S.A., 1988. Inventario de Glaciares del Perú. Primera parte. Hidrandina S.A., Unidad de Glaciologia e Hidrologia, Huaraz.

Jordan, E., 1991. Die Gletscher der Bolivianischen Anden. Franz Steiner, Stuttgart.

Kaser, G., Ames, A. and Zamora, M., 1990. Glacier fluctuations and climate in the Cordillera Blanca, Peru. Ann. Glaciol., 14: 136–140.

Kattelmann, R. and Elder K., 1991. Hydrologic characteristics and water balance of an alpine basin in the Sierra Nevada. Water Resour. Res., 27(7): 1553–1562.

Montes de Oca, I. (Editor), 1982. Geografía y Recursos Naturales de Bolivia. Montes de Oca, La Paz.

Paltridge, G.W. and Platt, C.M.R., 1976. Radiative Processes in Meteorology and Climatology. Elsevier, Amsterdam.

Roche, M.A., Aliaga, A., Campos, J., Pena, J., Cortes, J. and Rocha, A., 1990. Hétérogénéité des précipitations sur la Cordillère des Andes Boliviennes. In: H. Lang and A. Musy (Editors), Hydrology in Mountainous Regions I. Hydrological Measurements; the Water Cycle. Publ. No. 193, International Association of Hydrological Sciences, Wallingford, pp. 381–388.

Tapley, T.D. and Waylen, P.R., 1990. Spatial variability of annual precipitation and ENSO events in western Peru. Hydrol. Sci. J., 35(4): 429–446.

Thompson, L.G., Mosley-Thompson, E. and Morales Arnao, B., 1984. El Niño-Southern Oscillation events recorded in the stratigraphy of the tropical Quelccaya ice cap, Peru. Science, 226: 50–52.

Young, G.J., 1985. Overview. In: G.J. Young (Editor), Techniques for Predictions of Runoff from Glacierized Areas. Publ. No. 149, International Association of Hydrological Sciences, Wallingford, pp. 3–23.