Glacier recession on Cerro Charquini (16° S), Bolivia, since the maximum of the Little Ice Age (17th century)

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ABSTRACT. Cerro Charquini, Bolivia (Cordillera Real, 5392 m a.s.l.) was selected as a site to reconstruct glacier recession since the maximum of the Little Ice Age (LIA) in the central Andes. Five glaciers, located on differently exposed slopes, present comprehensive and well-preserved morainic systems attributed to former centuries. The moraines were dated by lichenometry and show a consistent organization on the different slopes. The past geometry of the glaciers was reconstructed using ground topography and aerophotogrammetry. Lichenometric dating shows that the LIA maximum occurred in the second half of the 17th century, after which the glaciers have receded nearly continuously. Over the last decades of the 20th century (1983–97), recession rates increased by a factor of four. On the northern and western slopes, glaciers receded more than on the southern and eastern slopes (by 78% and 65% of their LIA maximum area, respectively). The mean equilibrium-line altitude (ELA) rose by about 160 m between the LIA maximum and 1997. Recession rates were analysed in terms of climatic signal, suggesting that glacier recession since the LIA maximum was mainly due to a change in precipitation and that the 19th century may have been drier. For the 20th century, a temperature rise of about 0.6°C appears to be the main cause of glacier recession. Recent climatic conditions from 1983 to 1997 correspond to a mass deficit of about 1.36 m w.e. a^{-1}. If such conditions persist, the small glaciers below 5300 m a.s.l. in the Cordillera Real should disappear completely in the near future.

1. INTRODUCTION

Much evidence indicates that tropical glaciers were far more extensive in past centuries. This is especially true during the Little Ice Age (LIA), which is well documented for some mountain ranges in the Northern Hemisphere such as the European Alps and the Canadian Rockies (Le Roy Ladurie, 1967; Grove, 1988; Luckman, 2000), and also identified in the tropical Andes (Broggi, 1945; Hastenrath, 1981; Clapperton, 1983; Ames and Francou, 1995; Francou, 2004). In the Cordillera Real, many moraines attributed to the LIA exist below the present glacier snouts, and the maximum extent has been considered the most prominent phase of glacier advance of the entire Holocene (Gouze and others, 1986). However, few studies have yet been able to accurately date glacier fluctuations over this period (Solomina and others, in press). The large uncertainties involved in dating these glacier fluctuations are partly due to the dating method using ^{14}C (Gouze and others, 1986; Seltzer, 1992), an isotope with atmospheric production rates that have varied over recent centuries, precluding dating within the last 300 years (Reimer and others, 2004). Information obtained from ice cores retrieved in the Andes has made it possible to roughly estimate the LIA's limits between the 15th and the late 19th centuries (Thompson and others, 1986). However more accurate dating of glacier evolution within this period requires other proxies.

Moraines are often used to date fluctuations and to reconstruct glacier areas and volumes with good accuracy. In the tropics, moraines are well preserved because reworking by frost penetration in the ground and snowmelt is extremely limited. Moreover, time lags between glacier mass-balance variations and the dynamic response of the snouts are generally short, i.e. one to a few years (Francou and others, 2004), particularly for the small glaciers (<0.5 km^2) that represent about 80% of the glacier area of the Cordillera Real, Bolivia (Jordan, 1991). Thus the moraines deposited by these small glaciers are believed to represent the form of the glaciers in an equilibrium state.

The aim of this paper is to describe the glacier evolution since the LIA maximum for this tropical Cordillera using moraines dated by lichenometry and to infer climate changes from these fluctuations.

2. STUDY AREA

Cerro Charquini (16°17′ S, 68°09′ W) is located 20 km northeast of La Paz, midway between Glaciar Zongo and Glaciar Chacaltaya where a permanent observation programme involving mass-balance, hydrological and energy-balance measurements has been run for more than a decade (Francou and others, 1995, 2003; Wagnon and others, 1999).

Despite the relatively low elevation of the summit (5392 m a.s.l.), glaciers with similar morphology are present on the different slopes, allowing aspect effects to be analysed without interference from other factors. The Cerro Charquini glaciers are small (<0.5 km^2 in 1997) and, together with their moraines, are all located within the same 4430–5300 m a.s.l. elevation range (Fig. 1). Moraines extend 1.5 km and 200–450 m in elevation beyond the

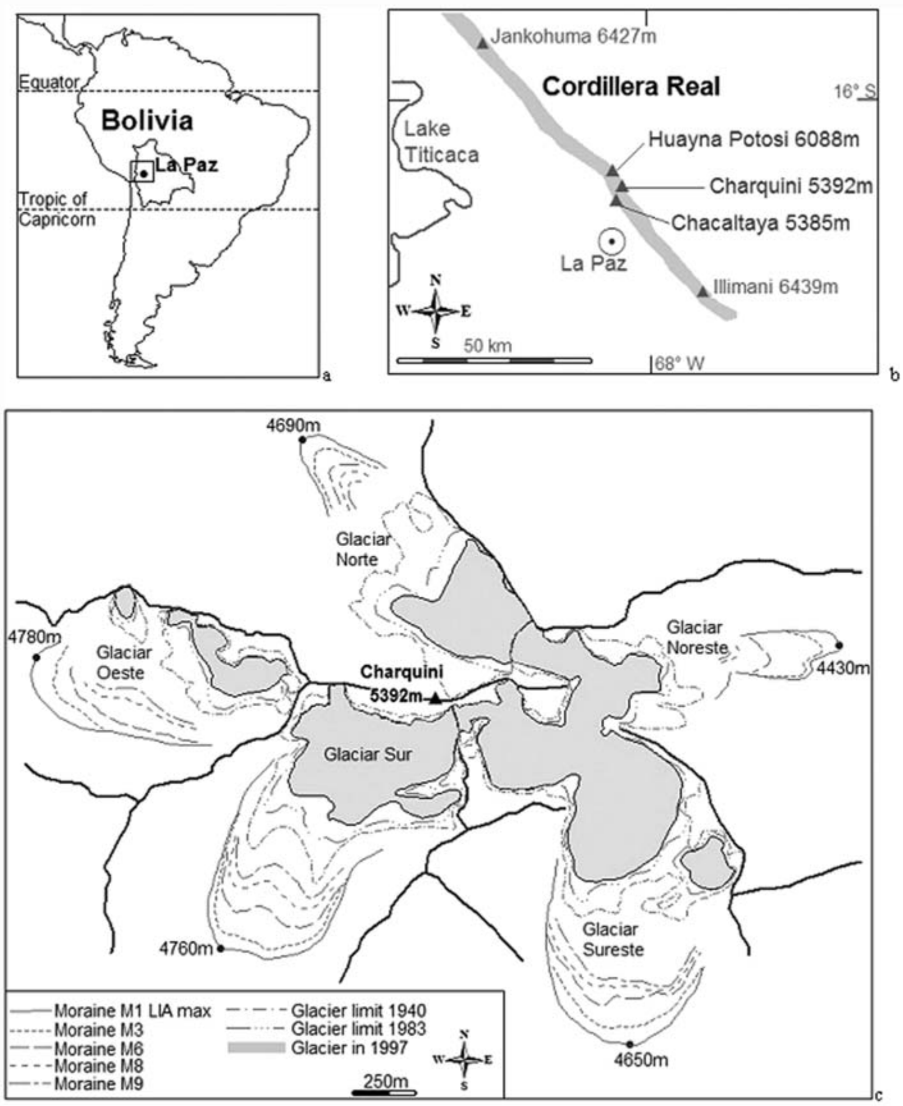

Fig. 1. Cerro Charquini glaciers (Cordillera Real, Bolivia, 16° S). Although the ten moraines can be found on each glacier foreland, only the five biggest (M1, M3, M6, M8 and M9) are shown. Glacier limits in 1940, 1983 and 1997 are from stereophotogrammetric restitutions.

present snouts. As they have not yet been covered by vegetation, these moraines may be considered, a priori, as dating from the LIA. Moraines and bedrock are granodiorites and quartzites, rock types that favour growth of *Rhizocarpon* sp., a lichen commonly used to date moraines worldwide (Innes, 1985).

In the Cordillera Real, annual precipitation amounts to 800–1000 mm at above 4000 m a.s.l., which falls generally as snow on the glaciers. Precipitation comes with humid air masses from the northeast, according to a mechanism called the Amazonian monsoon, and presents a very contrasted seasonal pattern, with 80% falling from October to April (austral summer) and 65% from December to February. This marked seasonality of the climate plays an important role in the mass-balance fluctuations. During the austral summer, accounting for 90% of the annual mass-balance variability (Francou and others, 2003), the maximum net accumulation occurs in the upper part of the glaciers while ablation rates are highest in the lower part. Ablation is associated with a strong total radiation influx to the glacier surface (the sun is vertical and cloudiness is maximum from November to February), high humidity and low winds (which limit sublimation) and a relatively high air temperature. Precipitation controls the energy balance at the glacier surface through the albedo (Wagnon and others, 1999). Every variation in the precipitation regime results in a change to the glacier surface albedo and consequently the ablation intensity (Sicart, 2002).

On a regional scale, the El Niño–Southern Oscillation (ENSO) controls the majority of the interannual variability of mass balance (Francou and others, 2003). Warm phases are generally accompanied by a precipitation deficit of 10–30% (i.e. less accumulation leading to a lower albedo), a decrease in cloudiness (i.e. more shortwave radiation reaching the glacier surface) and an increase in the sensible heat flux (air temperature anomaly in the +1° to +3°C range) (Wagnon and others, 2001). Consequently mass balance is very negative during El Niño years. An opposite situation occurs during the cold phases (La Niña), when mass balance shows near-equilibrium/positive values due to enhanced precipitation, colder air temperature and high cloudiness, which tend to decrease ablation strength and lower the ELA by 100–300 m compared with the warm phases. The climate during the LIA is believed to have been more extreme than at

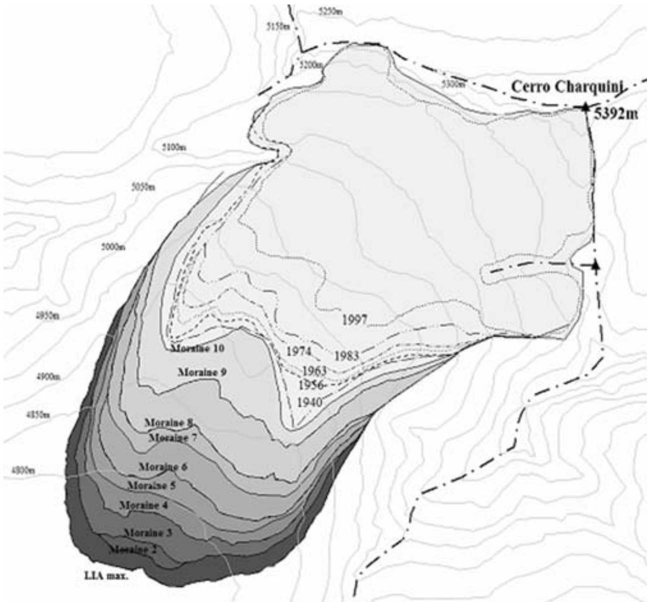

Fig. 2. Glaciar Charquini Sur. Surface area reconstructed on the basis of the moraines until M10 and by aerial photography from 1940.

present, and a direct effect of the ENSO variability during the last centuries on glacier fluctuations and moraine deposits has to be considered.

3. METHODS

3.1. Dating moraines by lichenometry

The dating of Charquini moraines by lichenometry with statistical analysis based on the extreme-value theory has been discussed elsewhere (Rabatel and others, 2005; Cooley and others, in press; Naveau and others, in press) and only the basic principles will be presented here.

The basic premise of lichenometry is that the diameter of the lichens growing on a surface is proportional to the length of time that the surface has been exposed to colonization and growth in a specific environmental context. Thus the largest lichens can be used to date the deposit, the stabilization or the exposure of surfaces.

All measurements were carried out with the *Rhizocarpon geographicum* s.l. lichen, which presents a circular growth pattern and has a lifetime longer than the period to be dated (Innes, 1985). Our dataset of lichenometric measurements is composed of 10 previously dated and 48 further surfaces. The surfaces of known age are presented in detail by Rabatel (2005). All were found in the eastern Cordillera (up to 4500 m a.s.l.), and so are expected to be representative of lichen growth rate on the glacier forelands. Eight date from the 20th century (between 1910 and 1965), one from the mid-18th century and one from the mid-17th century. Only the oldest one is based on a ^{14}C dating. All the others are dated using documentary sources. Undated surfaces correspond to the main moraines of each of the glaciers to be dated.

In the current study, a new method based on the extreme-value theory called generalized extreme values (GEV; Katz and others, 2002) was used to analyse lichenometric data. Maximum lichen diameters and average surface ages are assumed to have two different distributions, a GEV and a normal distribution, respectively. This statement is based on probability theory for maxima (extreme-value theory) and for averages (central limit theorem), respectively. These two distributions are linked through the relationship $\alpha = f(\mu)$, where the function f represents the temporal variation of μ (for more details see the papers mentioned above).

3.2. Reconstructing glaciers from moraines and aerial photographs

Glacier fluctuations during this period were reconstructed on the basis of moraines. All the moraines of the LIA and the beginning of the 20th century were dated by lichenometry. For the second part of the 20th century, five aerial photograph pairs dated 1956, 1963, 1974, 1983 and 1997 (Instituto Geográfico Militar, Bolivia) were processed using classical (non-digital) photogrammetric restitution techniques. This information allowed us to reconstruct glacier areas and to calculate volume changes. Aerial pictures from 1940 could not provide a three-dimensional restitution because the flight parameters were not available. Nevertheless, it was possible to calculate the glacier area of 1940 by plotting the limits on the 1/10 000 map based on other aerial photographs. Restitution was also used to obtain a complete 1/10 000 mapping of Charquini on which we represent the ten main LIA morainic stages for each of the five glaciers (see Fig. 2 which shows an example, Glaciar Charquini Sur). In order to validate the results of the restitution, a complete ground topographic survey of each moraine was performed on Glaciar Charquini Sur. Results of both methods are consistent and allow us to be confident that the mapping of glaciers and moraines for the whole Charquini area is accurate.

3.3. ELA reconstruction

The equilibrium-line altitude (ELA) was reconstructed for each morainic stage and each pair of photographs using the accumulation-area ratio (AAR) method and a ratio of 0.65 determined for Glaciar Zongo when mass balance is in equilibrium (1991–2004 series, see Soruco and others, 2005). This 2 : 3 ratio was also observed on other south-facing glaciers of the sector (Rabatel and Mendoza, 2004) and thus it can be considered as a realistic approximation for AAR_0 on a regional scale. Nevertheless this ratio is valid only on glaciers that are in equilibrium, and may change significantly according to slope aspect on the scale of the Charquini area.

3.4. Ice-volume and mass-balance reconstruction

For the ten LIA stages, glacier volumes were reconstructed by contour line interpolation based on the moraine height and the bedrock morphology. Since depth to the bedrock below the current glaciers was unknown, we could only calculate volume fluctuations between the different stages. For the 20th century, the volume variations computed from the photogrammetric restitution of each pair of photographs were considered to be accurate. After dating the moraines and aerial photographs, it was possible to calculate the mean annual mass balance for each period, given by the following equation:

$$\overline{B_{(T_i,\, T_{i+1})}} = \rho \frac{(V_{i+1} - V_i)}{(T_{i+1} - T_i) \times \frac{(S_{i+1} + S_i)}{2}} \,,$$

where $\overline{B_{(T_i,\, T_{i+1})}}$ is the mean annual mass balance for the period T_i to T_{i+1}, T_i is the glacier stage date (moraine or aerial

Table 1. Moraine dating by lichenometry with the associated error (years), surface area (km^2) and ELA (m a.s.l.) for the LIA stages and six 20th-century aerial photographs of the Charquini glaciers. On Glaciar Charquini Sureste blocks were too scarce on the M2 and M5 moraines to allow lichenometric measurements

	Charquini Sur			Charquini Sureste			Charquini Noreste			Charquini Norte			Charquini Oeste		
Moraine	Date	Surface area	ELA	Date	Surface area	ELA	Date	Surface area	ELA	Date	Surface area	ELA	Date	Surface area	ELA
LIA max	1686 ± 14	1.22	4930	1664 ± 14	1.41	4815	1662 ± 14	1.04	4870	1663 ± 14	1.06	4990	1663 ± 14	0.83	4910
M2	1703 ± 12	1.16			1.40		1700 ± 12	1.02		1706 ± 12	1.04		1700 ± 12	0.78	
M3	1734 ± 12	1.16	4935	1736 ± 12	1.38	4820	1740 ± 12	0.99	4885	1740 ± 12	1.02	4995	1739 ± 12	0.70	4915
M4	1765 ± 10	1.11		1755 ± 10	1.34		1758 ± 10	0.96		1755 ± 10	0.96		1755 ± 10	0.66	
M5	1802 ± 10	1.08			1.24		1767 ± 10	0.92		1769 ± 10	0.91		1763 ± 10	0.62	
M6	1808 ± 10	1.04	4965	1792 ± 10	1.22	4820	1794 ± 10	0.90	4910	1794 ± 10	0.88	5010	1791 ± 10	0.58	4930
M7	1825 ± 10	0.98		1819 ± 10	1.21		1817 ± 10	0.85		1817 ± 10	0.86		1815 ± 10	0.47	
M8	1843 ± 9	0.95	4985	1849 ± 9	1.20	4825	1848 ± 9	0.82	4920	1847 ± 9	0.85	5020	1852 ± 9	0.46	4950
M9	1871 ± 9	0.85	4995	1868 ± 9	1.18	4830	1864 ± 9	0.78	4940	1870 ± 9	0.83	5030	1873 ± 9	0.41	4965
M10	1912 ± 9	0.78	5025	1909 ± 9	0.94	4905	1905 ± 9	0.62	4950	1910 ± 9	0.66	5070	1907 ± 9	0.31	4980
Aerial photographs	1940	0.75	5030	1940	0.84	4925	1940	0.57	4965	1940	0.53	5110	1940	0.26	4990
	1956	0.71	5035	1956	0.79	4935	1956	0.51	4985	1956	0.42	5120	1956	0.24	5000
	1963	0.68	5040	1963	0.73	4940	1963	0.51	5000	1963	0.39	5130	1963	0.21	5010
	1974	0.65	5055	1974	0.69	4945	1974	0.48	5005	1974	0.35	5140	1974	0.18	5015
	1983	0.59	5075	1983	0.63	4950	1983	0.44	5010	1983	0.31	5145	1983	0.14	5020
	1997	0.49	5095	1997	0.52	4960	1997	0.36	5060	1997	0.23	5165	1997	0.11	5025

photograph), V_i, S_i are the volume and surface area for glacier stage i, and ρ is the ratio of ice density to water density (fixed at 0.9).

4. RESULTS

4.1. LIA chronology on Charquini glaciers

Only the principal results are presented here. Details about the interpretation of moraine dating can be found in Rabatel and others (2005). On the five glaciers the ten most important moraines were considered to determine the chronology of glacier evolution since the LIA maximum. The ten moraines can be found on all five slopes and show the same relative position and morphology (Fig. 1). Five moraines are always prominent (M1, M3, M6, M8 and M9) whereas the others (M2, M4, M5, M7 and M10) are less marked. The morphologies of the prominent moraines are believed to reflect phases of stabilization or small advances, whereas the others represent only short stops in a continuous recession process. By dating the moraines (Table 1), we found that the prominent outer moraine M1, which corresponds to the LIA maximum, was formed during the second half of the 17th century, i.e. between 1648 and 1700, taking into account the five slopes and the margins of error. The moraines M2, M3, M4 and M5, formed during the 18th century, reflect a gradual recession of glaciers, only interrupted by an advance which deposited moraine M3, which dated from 1722–52 depending on the glacier. In the late 18th to early 19th centuries (1781–1818), M6 attests to another advance. Then, during the first half of the 19th century, the glaciers retreated slightly and did not display an advance which could remove the older moraines. The long distance, more than 250 m on average, between the last moraine of the 19th century, M9 (about 1870), and M10 (about 1910), suggests an acceleration of the retreat during the late 19th century.

4.2. Ice surface area variations

Throughout the period extending from the mid-17th to the late 20th century, all the glaciers retreated over a distance of 950–1400 m. However, Glaciares Norte and Oeste lost much more (>78% of the maximum LIA area) than Glaciares Sur, Sureste and Noreste (<65%; see Table 1). Expressed in terms of annual means for the five glaciers, the area reduction was 0.15% a^{-1} between M1 and M9, increasing to 0.30% a^{-1} between M9 and M10. Afterwards, the retreat slowed during the first part of the 20th century (0.18% a^{-1}) then accelerated after the 1940s, reaching 0.35% a^{-1}. Since the beginning of the 1980s, the retreat rates (0.52% a^{-1}) have been the highest recorded over the last four centuries (Fig. 3). Between the LIA maximum and the late 19th century, the greatest retreats occurred on Glaciares Sur and Oeste. These glaciers lost 30–50% of the area of the LIA maximum while the others lost only 16–25%. Nevertheless, during the 20th century, Glaciares Norte, Noreste and Sureste retreated more than the others (40–57% vs 29–36%).

4.3. ELA fluctuations

Between the maximum LIA extent and the late 20th century, the ELA rise determined geometrically using the AAR method can be estimated at 158 ± 30 m (mean for the five glaciers) ranging from 115 m (for Glaciar Oeste) to 190 m (for Glaciar Noreste). The ELA rose from 4815–4990 m a.s.l. during the morainic stage M1 to 4960–5165 m a.s.l. during the last decades of the 20th century (Table 1).

Figure 4 shows that between the morainic stages M1 (~1665) and M3 (~1735) the ELA rise is very limited, less than 10 m. Its rise between M1 and M9 (~1870) is of the order of 50 m (ranging from 15 m on Glaciar Sureste to 70 m on Glaciar Noreste).

4.4. Volume variations and mass-balance changes

Figure 5 shows the mean annual mass balance, reconstructed for the following four periods: LIA maximum to late 19th

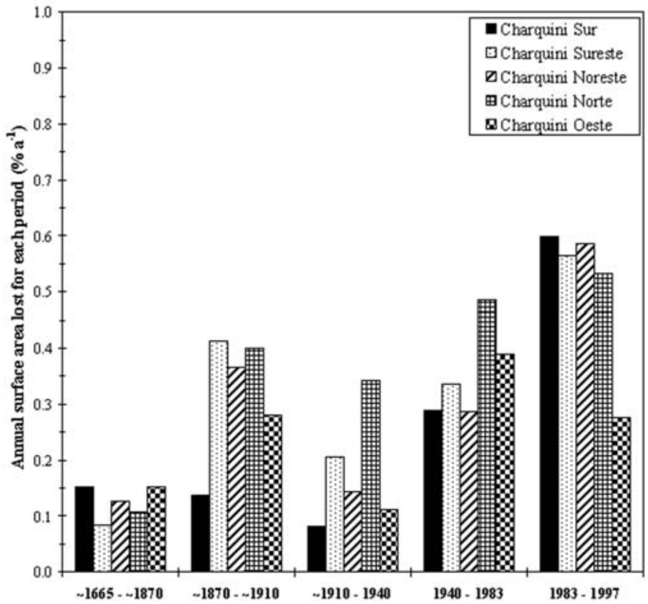

Fig. 3. Surface area lost for each period for the five Charquini glaciers. The area lost is given as a percentage of the initial area.

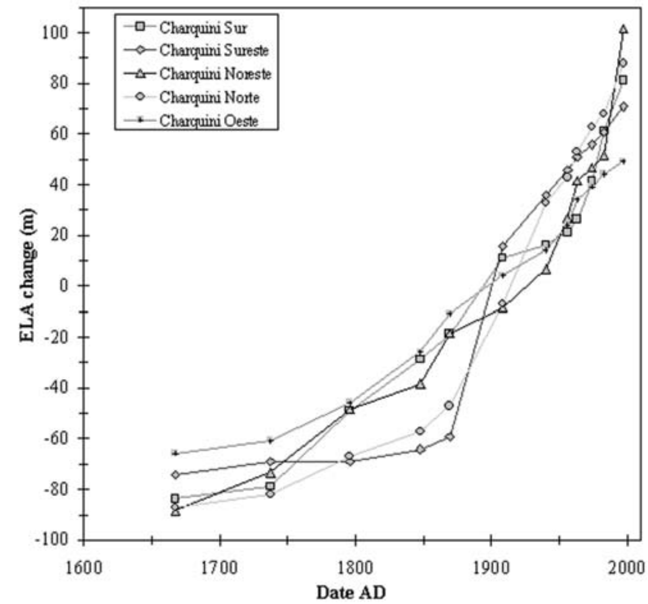

Fig. 4. Fluctuation of the ELA since the LIA maximum. The zero represents the average altitude of the ELA over the whole period.

century, late 19th to early 20th century, early 20th century to 1983 and 1983–97. This information leads to the same conclusions as the reconstructed areas. Between the LIA maximum and the late 19th century, ice loss was low, with a mean mass balance estimated at about –0.10 m w.e. a^{-1}. Between M9 and M10 (~1870 and ~1910), the mass balance of the five glaciers was, on average, four times more negative (–0.40 m w.e. a^{-1}). For the ~1910–1983 period, deficits were less pronounced, with an average of about 0.25 m w.e. a^{-1}. The last two decades of the 20th century marked a shift in the deficits, which increased to 1.36 m w.e. a^{-1} (average for the five Charquini glaciers). This clearly represents the largest mass loss recorded over the past four centuries, and it is also for the shortest time-scale. In addition, we observe that Glaciares Oeste and Norte present the strongest recession for recent years (1983–97) with losses as high as 3 and 2.3 m w.e. a^{-1}, respectively. However, Glaciar Oeste is believed to be less representative than the others because of its smaller size (<0.15 km^2) and because its low elevation puts it completely in the ablation zone. The three other glaciers facing east and south experienced clearly less negative mass balances that did not exceed –0.66 m w.e. a^{-1}.

5. DISCUSSION

5.1. Comparison with other glaciers in the central Andes

The chronology obtained for the Charquini glaciers indicates that recession of glaciers in the Bolivian Andes since their LIA maximum is in good agreement with that of glaciers in the Peruvian Cordillera Blanca (Solomina and others, in press). After the LIA maximum, in the second half of the 17th century, the Cordillera Blanca glaciers receded nearly continuously, with only minor readvances, each less than that which deposited the outer moraine M1. This recession occurred even during the early 19th century, when many Northern Hemisphere glaciers grew and sometimes exceeded their 17th-century maximum (Grove, 1988). Surface area losses since the LIA maximum on Charquini glaciers are consistent with those obtained on the nearby south-facing Glaciar Chacaltaya (0.035 km^2, 5395–5150 m a.s.l.), which in 1998 had lost 80% of its maximum LIA area (Ramírez and others, 2001). Similarly Hastenrath and Ames (1995a, b) found that Glaciar Yanamarey (0.8 km^2, 5200–4600 m a.s.l., facing southwest) in the Cordillera Blanca lost about 53% of its surface area between the LIA maximum (undated) and the early 1980s, consistent with Glaciar Charquini Sur which lost almost the same area (51%) over the same period. The accelerated retreat and very negative mean annual mass balance during the M9–M10 period could be the consequence of a significant climate change. Both support the idea that the LIA ended between about 1870 and 1910. This result is consistent with evidence of rapid glacier decrease in other places of the tropical Andes in Peru and Ecuador, as reported by voyagers and scientists of the late 19th century (Broggi, 1945; Hastenrath, 1981; Ames and Francou, 1995; Francou, 2004).

Several studies of 20th-century recession have been performed in Peru (Cordillera Blanca and Cordillera de Vilcanota) by Broggi (1945), Kinzl (1969), Brecher and Thompson (1993), Hastenrath and Ames (1995a, b) Kaser and Georges (1997) and Thompson and others (2000). In the Cordillera Blanca, glacier retreat accelerated after the 1890s (Kinzl, 1969). Then it slowed down during the first half of the 20th century, with a small but marked readvance in the 1920s. This event was followed by another significant retreat in the 1930s–1940s (Broggi, 1945; Kaser and Georges, 1997; Georges, 2004). During 1950–1970, glaciers retreated very slowly (Hastenrath and Ames, 1995b), followed by a general acceleration (Ames and Francou, 1995; Kaser and Georges, 1997). For the Cordillera de Vilcanota, Brecher and Thompson (1993) and Thompson and others (2000) noted that the Qori Kalis, a glacier issuing from the Quelccaya ice cap, receded between 1963 and 1998. The retreat increased after 1980. The area lost was 8.4 times greater between 1983 and 1991 than during the 1963–78 period, and the retreat accelerated dramatically during the 1990s. For the Bolivian eastern Cordillera, the recession of the Charquini glaciers can be summarized in four stages: (1) a major retreat starting in the late 19th century; (2) a relative slowdown during the 1910s/1930s; (3) an acceleration since the 1940s; and (4) a very strong recession during the 1980s/1990s. Thus, the consistency of glacier fluctuations observed throughout the tropical Andes between the late 19th and the 20th centuries highlights that glaciers appear to respond to the same climatic signal on a regional scale.

5.2. Climatic interpretation

From the mid-17th to the late 19th century

Whatever their aspect, the Charquini glaciers have evolved in a similar way since their LIA maximum and their retreat has been practically continuous since the second half of the 17th century. The presence of many morainic ridges shows that the retreat was interrupted by several periods of stabilization or small advance, but these advances were never large enough to bury the moraines deposited previously. Being similar in size, morphology and elevation, the main parameter which may determine fluctuations of different magnitudes for these glaciers is their aspect, which controls precipitation amounts, cloudiness and radiative fluxes. Thus, variations from one glacier to another can be interpreted in terms of climate influence.

According to the sensitivity analysis carried out by Hastenrath and Ames (1995a) on Glaciar Yanamarey in Peru and assuming melting to be the only ablation process (with a latent heat of melting $L_m = 33 \times 10^4\,\mathrm{J\,kg^{-1}}$), the Charquini glaciers' mean annual balance value between the LIA maximum and the late 19th century of –0.10 m w.e. translates to increasing energy absorbed by the glacier surface of about $1\,\mathrm{W\,m^{-2}}$. This excess energy could have been the consequence of a rise in temperature of 0.15°C, an additional humidity of $0.05\,\mathrm{g\,kg^{-1}}$, a decrease in cloudiness of about 0.1/10, or a combination of these variables. The increase in incoming solar radiation caused by a decrease in cloudiness can explain the strong sensitivity of glaciers to a change in this parameter. However, the resulting decrease in incoming longwave radiation can offset this effect (Ambach, 1974). It is thus difficult to determine the exact influence of changes in cloudiness on the glacier surface energy balance. A change in cloudiness can also affect precipitation and thus the glacier surface albedo (assuming that precipitation falls in mainly solid form on the glacier) but such a small change is hardly quantifiable. However, these two parameters (less cloudiness plus less precipitation) are linked and even with a slight shift they may sum their effects to increase melting at the glacier surface. If the glacier retreat between the LIA maximum and the late 19th century was the result of a 0.15°C rise in temperature, the resulting ELA shift according to Kaser's model linking ELA to climate variables (Kaser, 2001) would have been only 20 m, inconsistent with the 50 m found on Charquini glaciers. In the model of Kaser (2001) a change of the ELA can be interpreted in terms of changes in accumulation, energy balance and temperature or any combination of these variables. Considering change in accumulation only, this 50 m ELA shift between the LIA maximum and the late 19th century (of which 42 m was between M3 (~1735) and M9 (~1870)) could have been the consequence of a decrease in annual accumulation of about 340 mm. Taking into account both temperature and precipitation changes, with a temperature rise of 0.10°C

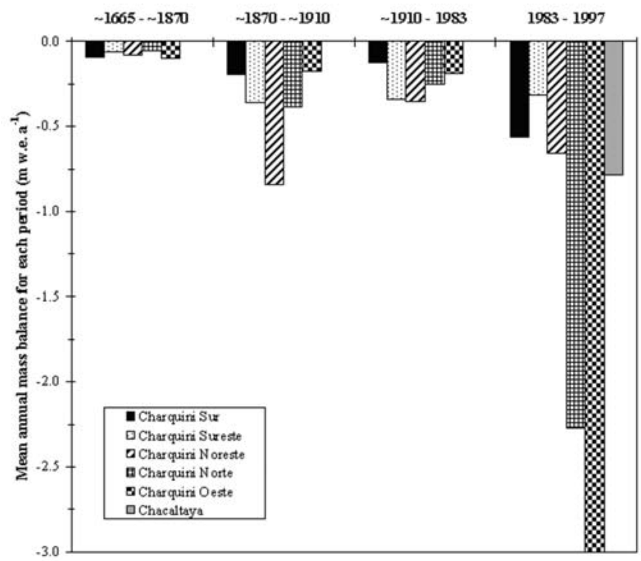

Fig. 5. Mean annual mass balance reconstructed for each period for the five Charquini glaciers. The value for Glaciar Chacaltaya is shown for the 1983–1997 period for comparison.

(i.e. two-thirds of the sensitivity analysis from Hastenrath and Ames) the decrease in accumulation between M1 (~1665) and M9 (~1870) becomes 210 mm. This change represents a decrease of 20–25% of the present accumulation amount. This is consistent with the results of Thompson and others (1986) based on the Quelccaya ice core that showed an accumulation deficit of about 20% of the present average amounts during the 1720–1860 period.

Furthermore, as noted in section 4, Glaciares Oeste and Sur exhibited the greatest retreat and the most negative mass balance between the LIA maximum and the late 19th century, a trend which was particularly marked during the 19th century. Precipitation and cloudiness coming from the northeast are crucial for mass balance (section 2). Lower accumulation on the leeward slopes than on the northeast-facing slopes (Rabatel and Mendoza, 2004) leads to a reduced albedo on Glaciares Sur and Oeste. Since cloudiness follows the same pattern, these slopes experience a higher shortwave radiation influx which, combined with the reduced albedo, causes greater energy absorption by the glacier surface. In the tropics, the energy available to melt snow and ice is particularly high on southern slopes during summer when the sun is at its highest (Francou and others, 1995). The recent energy balance measured year-round on Glaciar Zongo by Wagnon and others (1999, 2001) shows that the consequences of a precipitation/cloudiness deficit during the austral summer are considerable for the glacier. Therefore, considering the importance of precipitation deficits on glacier mass balance nowadays, the assumption that the mid-18th to late 19th centuries could have been dry is reasonable.

Strengthening the findings of Thompson and others (1986) about a dry 19th century, Valero-Garces and others (2003) have pointed out a precipitation deficit during the late 19th to early 20th century from palaeohydrological reconstructions based on sedimentological, geochemical and isotopic records in the Bolivian Altiplano. This evidence is also consistent with the historical ENSO records (Quinn and Neal, 1992; Ortlieb, 2002) which revealed that the last decades of the 19th century were marked by strong and long-lasting ENSO warm events. As pointed out in section 2, melting accelerates dramatically during the ENSO warm phases. The El Niño occurrence during this period is thus consistent with the accelerated retreat observed on the Charquini glaciers (section 4.2 and 4.4) and throughout the central Andes.

The 20th century

For the 20th century, a 100 year record (from 1898) of precipitation in La Paz (San Calixto station, 3660 m a.s.l., 20 km south of the Charquini massif) recently analysed by Gioda and others (in press) did not display any significant trend over this period. In consequence, the estimated –0.4 m w.e. a^{-1} mean annual mass balance for all the Charquini glaciers over the 20th century, corresponding to an increasing energy at the glacier surface of 4 W m^{-2}, could have resulted principally from a rise in temperature of 0.57°C according to the mass-balance sensitivity analysis. According to Kaser's model, the 110 m rise of the ELA (mean of the five glaciers) corresponds to a rise of 0.6°C, assuming only a change in temperature. Note that both results of air-temperature rise are consistent with the 0.55°C warming generally estimated in the literature over the same period (Lean and others, 1995). Thus, in contrast to the mid-17th to late 19th centuries, the recession of glaciers during the 20th century appears to have been the result of increasing air temperature.

Consistent with this hypothesis is the more severe retreat throughout the 20th century observed on Glaciares Norte and Oeste. Since the snouts there were 150 m lower at the end of the 19th century than on southern and western slopes, a rise in temperature, which controls the altitude of the snow/rain limit, might have led to higher ablation rates and consequently to a more rapid retreat of these tongues.

During the last two decades of the 20th century, the acceleration of glacier retreat is here, as elsewhere in the tropical Andes, coincident with the Pacific climate shift of 1976 after which the El Niño frequency and intensity increased significantly (Francou and others, 2003, 2004). The mean annual mass balance over the 1983–97 period was about –0.51 m w.e. a^{-1} for Glaciares Sur, Noreste and Sureste and as high as –2.64 m w.e. a^{-1} for Glaciares Norte and Oeste. This represents an increase in energy available at the glacier surface of about 5 W m^{-2} for Glaciares Sur, Sureste and Noreste and 28 W m^{-2} for Glaciares Norte and Oeste. Depending on the slope, the possible causes of the rapid glacier retreat in the late 20th century appear to be a rise of 0.8–3°C in air temperature (enhancing sensible heat transfer to the glacier), an increase in specific humidity of 0.3–1.5 g kg^{-1} (reducing sublimation and increasing melting), a decrease in cloudiness of less than 0.5/10 to 1/10 (increasing solar radiation) or any combination of these processes.

5.3. The imbalance of Charquini glaciers

The assumption that moraine deposits represent glaciers in an equilibrium state is valid for small glaciers. It is therefore appropriate to determine the ELAs 'geometrically' from glacier areas between the LIA maximum and the first part of the 20th century. However, the method is spurious when glaciers are in a constant and rapid recession and hence markedly unbalanced, as occurred during the last decades of the 20th century. In this situation, the snout fluctuations reflect ablation conditions in the lower zone rather than oscillations of the ELA, which are generally located at the top of the glacier or above. In that case a comparison of the ELAs calculated using the AAR method with those determined from field observations (ablation stakes) shows how unbalanced these glaciers are in relation to the present climate and how rapid their shrinkage will be in the near future (Ramírez and others, 2001). From ablation stakes during the 1991–2004 period, the ELA_0 is observed on Glaciar Zongo (facing south to east) and Glaciar Chacaltaya (facing south) at 5215 m a.s.l. (Soruco and others, 2005). Calculated for glaciers of similar aspect on the Cerro Charquini using the AAR method for 1997, the ELA is found at 4960–5095 m a.s.l. That is a difference between direct measurements and the AAR calculation of about 120 m for the southern slopes and about 250 m for the southeastern slopes. This average difference of 175 m represents the imbalance of the Charquini glaciers under current climatic conditions. Due to the small gap existing between their mean ELA and the maximum elevation of their upper reaches, these glaciers could recover equilibrium in the future only by a drastic reduction in their area. This implies that the Charquini glaciers, and in general all the glaciers of the Cordillera Real extending below ~5300 m a.s.l., are unbalanced under the present climate and could disappear in the near future.

6. CONCLUSIONS

A new chronology and a quantification of the glacier recession since the LIA maximum have been presented in this study from the Charquini area in the Bolivian Andes. Surface area, ELA, volume and mass balance were reconstructed using well-preserved moraines dated by lichenometry and using photogrammetry for the last six decades of the 20th century.

The LIA culminated during the second half of the 17th century and glaciers subsequently retreated nearly continuously. Retreat slowed down during the early 19th century but no important readvances occurred.

The major acceleration of glacier recession observed between M9 and M10 suggests the LIA ended between about 1870 and 1910, consistent with evidence found throughout the Andes and in many places in the Northern Hemisphere.

The retreat between the LIA maximum and the late 19th century was probably associated with a significant decrease in precipitation and cloudiness, particularly during the 19th century.

In contrast, a sensitivity analysis shows that glacier retreat during the 20th century has been principally due to a rise in air temperature of about 0.57°C. In order to reverse the present deficit and to balance these glaciers, a decrease in energy available for melting ice of about 28 W m^{-2} would be required. This exceeds the current climatic variability.

The AAR method suggests the ELA might have been on average 158 m lower during the second half of the 17th century (LIA maximum) than during the last decades of the 20th century, assuming that current glacier geometry corresponds to a steady state of the glaciers.

The ELA measured on nearby Glaciar Zongo for the 1991–2004 period (i.e. 5215 m a.s.l.) differs from the ELA geometric computation based on the AAR method by 175 m; this difference shows that the current glacier extent does not correspond to a balanced situation. It can be deduced that the Charquini glaciers, as well as all the small glaciers of the Cordillera Real below 5300 m a.s.l., are not in equilibrium with the present climate and that they could disappear in the next few decades. This confirms the assertion from Glaciar Chacaltaya (Ramírez and others, 2001).

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