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A chronology of the Little Ice Age in the tropical Andes of Bolivia (16°S) and its implications for climate reconstruction

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Abstract

Dating moraines by lichenometry enabled us to reconstruct glacier recession in the Bolivian Andes since the Little Ice Age maximum. On the 15 proglacial margins studied, we identified a system of ten principal moraines that marks the successive positions of glaciers over the last four centuries. Moraines were dated by performing statistical analysis of lichen measurements based on the extreme values theory. Like glaciers in many mid-latitude mountain areas, Bolivian glaciers reached their maximal extent during the second half of the 17th century. This glacier maximum coincides with the Maunder minimum of solar irradiance. By reconstructing the equilibrium-line altitude and changes in mass-balance, we think the glacier maximum may be due to a 20 to 30% increase in precipitation and a 1.1 to 1.2 °C decrease in temperature compared with present conditions. In the early 18th century, glaciers started to retreat at varying rates until the late 19th to early 20th century; this trend was generally associated with decreasing accumulation rates. By contrast, glacier recession in the 20th century was mainly the consequence of an increase in temperature and humidity. These results are consistent with observations made in the study region based on other proxies.

Keywords: Little ice age; Moraines; Lichenometry; Glacier fluctuations; Climate reconstruction; Tropical Andes; Bolivia

Introduction

The concept of Little Ice Age (LIA) was introduced by Matthes (1939) on the basis of glacier advances that occurred between the 16th and 19th centuries. Although these advances were well documented in many mountains in the Northern Hemisphere, data remain very scarce for the tropics (Grove, 1988). Thus, many uncertainties persist concerning the timing of glacier fluctuations and the type of climate that triggered them. Were glacier fluctuations during the LIA in the tropics of the same magnitude as those in mid-latitudes? Were these fluctuations synchronous with others observed elsewhere, suggesting that climate changes during this period were similar and produced the same effects worldwide? Documenting the LIA in the central Andes is very important to understand the origin of the LIA and to strengthen climatic reconstructions in the tropics, where proxies from continental environments are scarce and difficult to interpret. The present study is a component of the international IGBP-PAGES initiative called "*Long-Term climate REconstruction and Diagnosis of southern South America (LOTRED-SA)*" a collaborative, high-resolution multi-proxy approach to produce a regional climate reconstruction for the last 1000–2000 years (Grosjean and Villalba, 2005).

In recent papers, we presented a chronology of moraines for glaciers of the Charquini, Bolivia (Rabatel et al., 2005) and the reconstruction of their evolution in terms of surface area, equilibrium-line altitude (ELA), volume and mass balance (Rabatel et al., 2006). The aims of the present study were: i) to

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extend the analysis of glacier evolution to the whole Bolivian Eastern Cordillera using a larger number of proglacial margins in order to test the coherence of our previous results, and to propose a reference chronology of the LIA for this tropical cordillera; and ii) to use the proposed chronology to deduce climate changes that occurred during and after the LIA using simple glacier–climate models tested on monitored glaciers in the same area.

LIA in the tropical Andes

There is plenty of evidence that glaciers in the tropical Andes were much more extensive during the LIA than today (Hastenrath, 1981; Clapperton, 1983) but up until now the date of their maximum extent and the stages of their subsequent retreat remain very conjectural. Historical sources (Broggi, 1945; Francou, 2004) and mining settlements established in the colonial period (Pflücker, 1905) indicate that glaciers advanced considerably during the 16th–19th centuries, then began to retreat after AD 1860 in Peru (Ames and Francou, 1995) and Ecuador (Hastenrath, 1981). Based on these reports and on field observations, but with no access to dating methods, the LIA maximum in the tropical Andes was generally assumed to have occurred either in the middle (Kaser, 1999) or at the end of the 19th century (Kinzl, 1965), or even during the early 20th century (Lliboutry et al., 1977).

Some authors tried to date the LIA in the tropical Andes from glacier evidence using ^{14}C dating. In Bolivia, Gouze et al. (1986) suggested 670–280 cal yr BP as the interval displaying the maximal ice extension. In Peru, Thompson et al. (1986) suggested the LIA lasted between AD 1500 and 1900 on the basis of evidence found in the ice core retrieved on the Quelccaya ice cap.

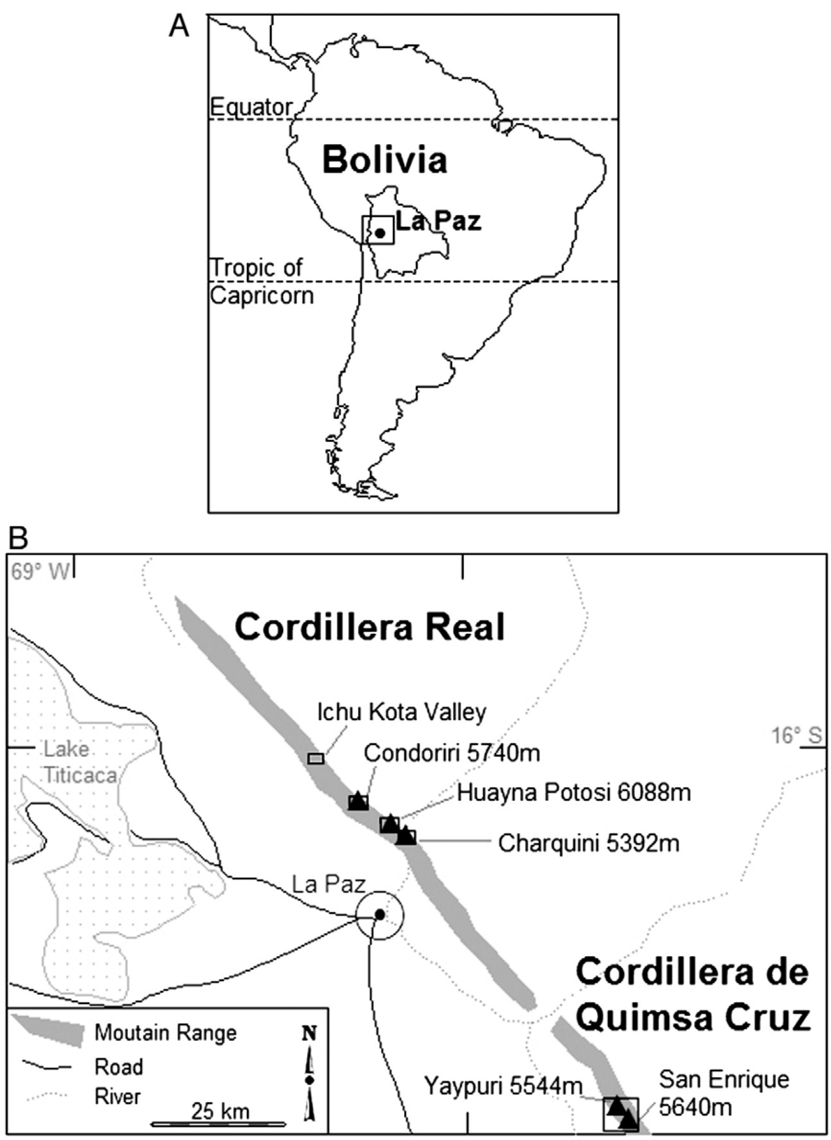

Figure 1. Study area: General map (A and B), Charquini Massif (C), Huayna Potosi Massif (D), Condoriri Massif (E), Ichu Kota Valley (F), Quimsa Cruz Massif (G). Although 10 moraines were found on each glacier foreland, only the five biggest (M1, M3, M6, M8 and M9) are shown here.

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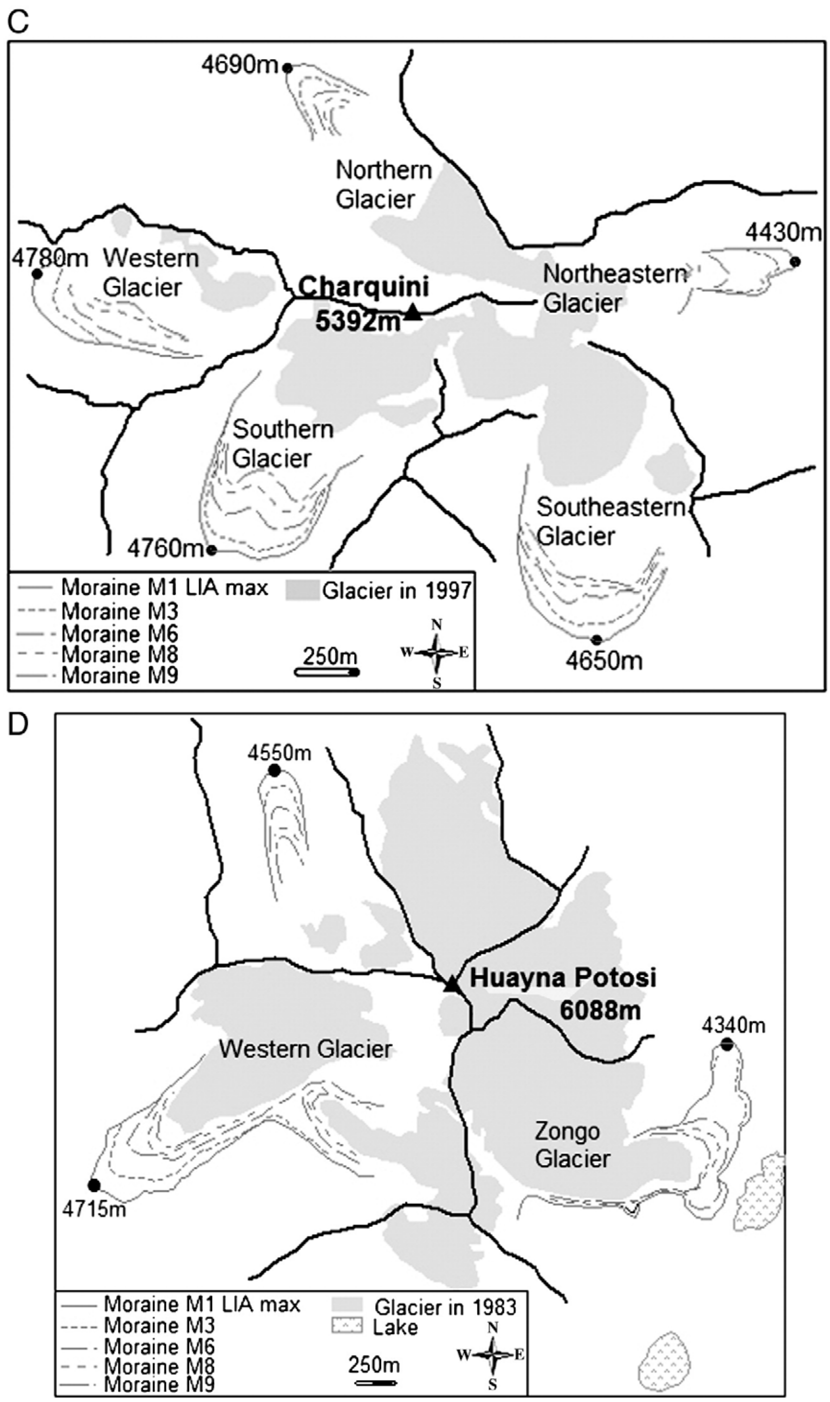

Figure 1 (*continued*).

Recently, Polissar et al. (2006) presented evidence for four glacial advances between AD 1250 and 1810 in the Venezuelan Andes based on lake-sediment analysis. But this method did not enable the authors to specify when glaciers were at their maximum or minimum extent.

The presence of very well preserved moraines on glacier forelands makes it possible to fill this gap and to offer a detailed chronology of glacier fluctuations. Lichenometry provides a reliable technique for dating using *Rhizocarpon sp*., which grows up to 5000 m asl in this terrain. The method was first used in the tropics by Rodbell (1992) in the Peruvian Cordillera Blanca to establish a chronology of Holocene glaciations. Rodbell described several morainic ridges deposited in the Holocene, but only the ridge located closest to current glacier snouts was linked to the LIA. Dates reported for these moraines (AD 750 to 1900) did not allow the author to present a detailed chronology of glacier fluctuations during this period. The first lichenometric study focussing on the LIA was performed in

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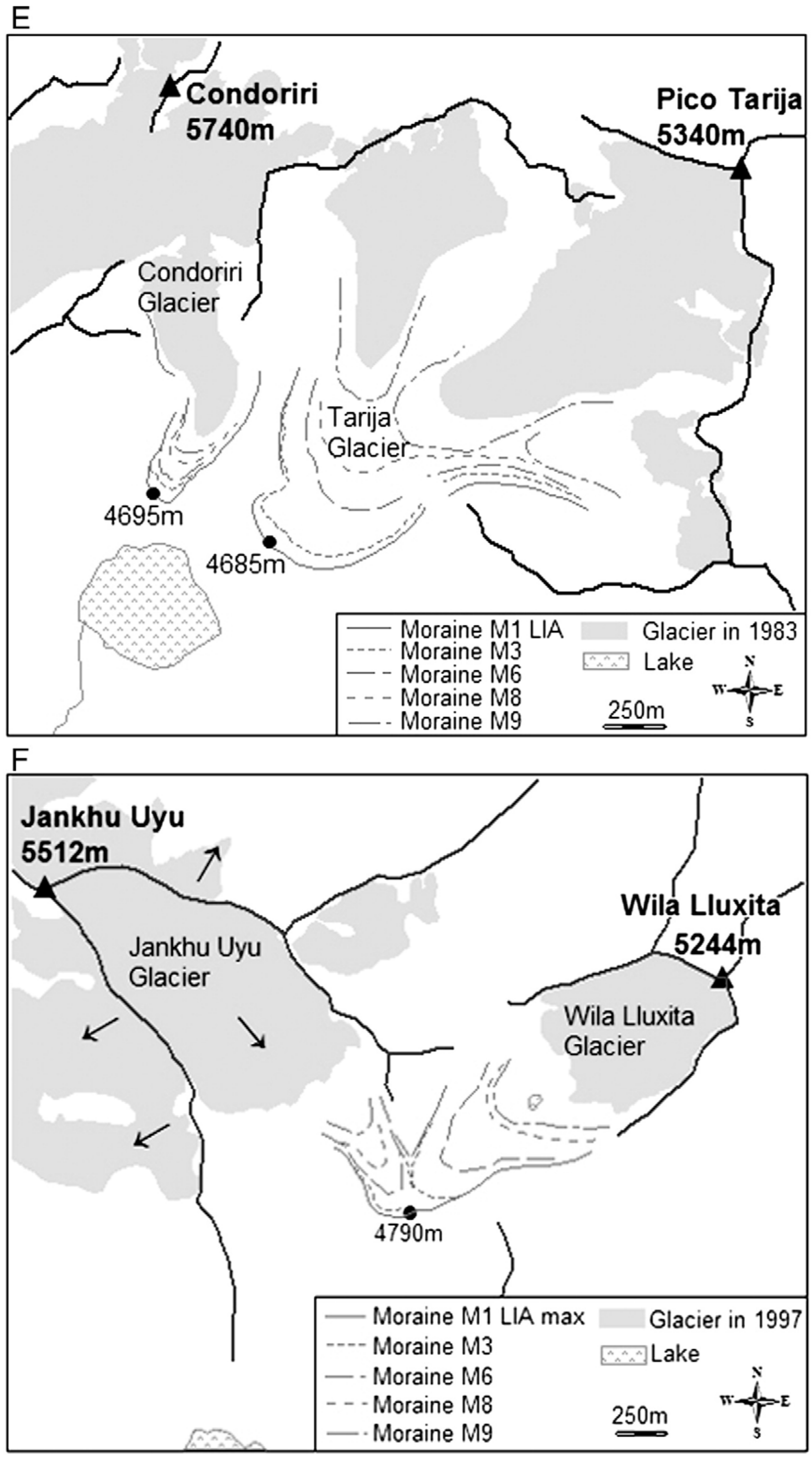

Figure 1 (*continued*).

the same Cordillera Blanca by Solomina et al. (2007). These authors improved the results obtained by Rodbell by revealing a clear glacier maximum between AD 1590 and 1720 followed by minor advances between AD 1780 and 1880. By reassessing LIA moraine ages previously obtained by Solomina et al. (2007), using the same statistical analysis as the one used here, Jomelli et al. (in press) dated the maximum glacial advance in the Cordillera Blanca from AD 1630±27.

Recently, we presented a detailed chronology of LIA glacier evolution in the tropical Andes based on a case study in Bolivia (Rabatel et al., 2005; 2006). Using five glaciers forelands, we showed that the LIA glacier maximum occurred in the second half

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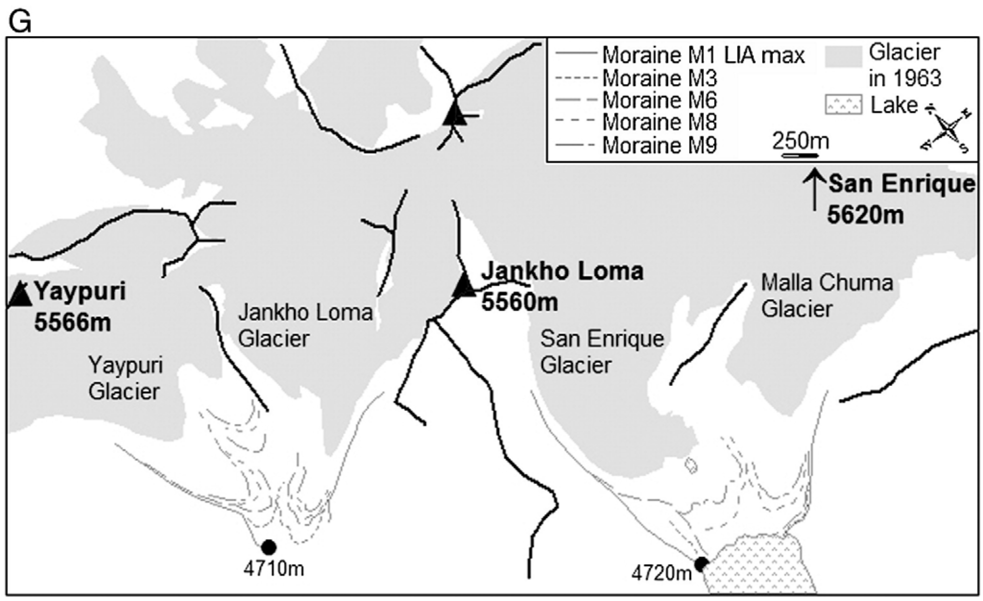

Figure 1 (*continued*).

of the 17th century. Glaciers kept a large extension until about AD 1735, and then began to recede at rates that varied with the period.

Study area

Climatic setting

Climate of this tropical cordillera is characterized by a low annual temperature range (<5°C) with a slight peak in summer (December–February) when extraterrestrial radiation and air moisture are at their maximum. Incident solar radiation is strong all year round and not very seasonally contrasted due to the low latitude and because at its maximum (in summer) it is attenuated by pronounced cloudiness. On the other hand, when incident solar radiation is minimum (May–August), the atmosphere is dry and cloudiness is not a limiting factor.

In contrast, seasonality of humidity and precipitation is very strong. Humid and precipitation fluxes come from the northeast via the Amazonian basin and (measured) precipitation can reach 800–1000 mm yr^{-1} on the glacier at low elevation. The October–December period is characterised by a progressive increase in moisture and precipitation. Accumulation rates reach maximum between January and April (2/3 of the total amounts). The period between May and September is characterized by a dry atmosphere, strong westerly winds at high elevations, low cloudiness, and cooler temperatures.

The seasonal pattern displays significant modifications due to climatic variability. At the decadal time scale, climate variability is mainly controlled by El Niño Southern Oscillation (ENSO) phases (Francou et al., 2003). The warm El Niño phase results in a significant decrease in precipitation during the austral summer. The reduction in precipitation before February–March delays snow cover (Wagnon et al., 2001). By contrast, during La Niña periods, snow cover on glaciers is maintained from October/November to April/May due to regular snowfall, increased cloudiness and lower temperatures.

Behaviour of tropical glaciers

Continuous monitoring of the Zongo glacier by IRD since 1991 has revealed the key factors of mass-balance variability (Wagnon et al., 1999; Sicart, 2002). These factors are: 1) precipitation through accumulation in the upper glacier and feedback mechanisms on the albedo, which controls ablation in the lower glacier; 2) cloudiness, which decreases short-wave radiation during the wet season; and 3) relative humidity, which modulates the energy transfer from melting to sublimation.

These parameters are strongly affected by ENSO (Francou et al., 2003). During El Niño phases, the combined effect of precipitation deficit, decrease in cloudiness and increase in heat flux increases melting of glacier surface even above 5300 m asl. Consequently, the mass balance is very negative (Wagnon et al., 2001). By contrast, during La Niña phases, glacier mass balance can be close to equilibrium or even positive.

Glaciers and moraine systems sampled for this study

The Cordillera Real and Cordillera de Quimsa Cruz are part of the Bolivian Eastern Cordillera (Figs. 1A and B). Many summits reach more than 6000 m asl. Due to the low latitude, glaciation is reduced and glaciers are small (80% cover less than 0.5 km^2). The Eastern Cordillera is made up of an intrusive granodiorite, a substratum that enables widespread growth of the *Rhizocarpon sp* which can thus be used to date surfaces.

Fifteen glaciers were selected in both Cordillera Real and Cordillera de Quimsa Cruz (Table 1): eleven in the Cordillera Real (five on the Cerro Charquini, Figure 1C; two on the Cerro Huayna Potosi, Figure 1D; two on the Cerro Condoriri, Figure 1E; two in the upper part of the Ichu Kota Valley, Figure 1F), and four in

Table 1
Characteristics of the 15 glaciers studied

	Ichu Kota glaciers		Charquini glaciers					Huayna Potosi glaciers		Condoriri glaciers		Quimsa Cruz glaciers			
	Jankhu Uyu	Wila L.	Southern	South-E.	North-E.	Northern	Western	HP West	Zongo	Condoriri	Tarija	Malla C.	San Enrique	Jankho L.	Yaypuri
Surface area (km²)	0.335	0.329	0.493	0.521	0.359	0.232	0.108	2.156*	2.360*	0.444*	1.553*	Unknown	Unknown	Unknown	Unknown
Aspect	S–E	S–W	S–S–W	E–S–E	E	N–N–W	W–S–W	S–W	S–E	S	S–W	W	S–W	S–W	S
Summit (m asl)	5450	5240	5350	5350	5300	5260	5150	5450*	5950*	5530*	5320*	5550	5500	5550	5450
Snout (m asl)	5100	5000	4960	4830	4870	5070	4950	4880*	4850*	4790*	4740*	5000	4900	4950	5050

For Quimsa Cruz glaciers data results from field measurements made in 2004.
Data are from the photogrammetric restitution in 1997 or 1983*.

the Cordillera de Quimsa Cruz (Cerros Yaypuri and San Enrique, Fig. 1G). Morainic systems were selected with a view to capturing the respective effects of slope exposure (all are represented), glacier sizes (between 0.1 and more than 2 km^2 in 1997), and spatial fluctuations in LIA glaciers evolution throughout the cordillera (16°S–17°S).

Every glacier presents several well-preserved moraines located about 1 km below present snouts that indicate past extents (Fig. 1). As they are not yet covered by vegetation, these moraines can be considered to date from recent centuries. Moreover, moraines are well preserved thanks to the limited impact of erosion by flowing water and frost penetration. According to recent observations on glaciers in this region, the delay between mass-balance variations and dynamical response of snouts is short (Francou et al., 2004). Thus, moraines are believed to represent glaciers close to the equilibrium.

Methods

Moraine dating

To reconstruct the chronology of glacier fluctuations, a systematic morphostratigraphic analysis of the main moraines was performed using the following criteria: 1) the shape of moraines (size, height, slope of the outer and inner side); 2) the continuity of ridges on the proglacial margin; 3) any and evidence that moraines have (or have not) removed previous deposits; 4) the position of moraines along the glacier foreland.

To date moraines, lichens of *Rhizocarpon sp*. were measured both on moraines and on dated surfaces to compute the relation between lichen diameter and age. A detailed description of the sampling method can be found in Rabatel (2005) and Rabatel et al. (2005). Lichens selected for sampling were the biggest growing on the surfaces; they can therefore be considered as extreme values (Naveau et al., 2005; 2007). Consequently, we chose to process our data using a statistical method based on extreme values (General Extreme Value distribution called GEV) and Bayesian approaches. Our choice is also based on the results presented by Jomelli et al. (2007), who demonstrated by comparing different methods used in lichenometry that the GEV approach has three advantages: 1) the statistical method is appropriated to the type of data (i.e., extremes), 2) the accuracy of estimated dates is better than with other methods, and 3) the GEV approach allows to compute uncertainties on the given ages.

The statistical theory was extensively detailed in Cooley et al. (2006) and Naveau et al. (2007). Here we summarize only the main principles.

To implement the data, the strategy is to describe the largest lichen diameters by modelling the entire distribution of lichen measurements. The GEV distribution depends on three parameters and can be summarized as follows:

$$G(x;\mu,\sigma,\xi) = \begin{cases} \exp\left\{-\left[1+\xi\dfrac{x-\mu}{\sigma}\right]_{+}^{-1/\xi}\right\}, & \text{when } \xi\neq 0 \text{ and } a_{+}=\max(0,a), \\ \exp\left\{-\exp\left(-\dfrac{x-\mu}{\sigma}\right)\right\}, & \text{when } \xi=0, \end{cases} \quad (1)$$

where μ, σ, ξ, are the location, scale, and shape of the distribution, respectively. Maximum lichen measurements can be modelled by varying the distribution of GEV parameters as a function of moraine location and age. The parameter ξ is constant (Naveau et al., 2005). The two other parameters (μ and σ) are a function of the age of the moraine. Thus each sample surface is characterised over time, by letting the GEV location and shape parameters vary as a function of the age of the surface; and in space, by fixing the scale parameter. Based on this procedure a Bayesian model is built, i.e., the GEV and growth function parameters are treated as random variables with prior distributions (these prior distributions come from information about dated surfaces and biological knowledge). A Monte Carlo Markov Chain (MCMC) procedure is applied. The convergence properties of MCMC allow a good approximation of posterior distribution (Cooley et al., 2006) of parameters after a large number of iterations (more than 100,000 in our case). At each iteration, all parameters (GEV and growth curve parameters), are updated one-at-a-time until the best combination of parameters is found. This enables an empirical distribution to be computed for each parameter. In particular, the posterior age distribution of each undated surface is provided. Confidence intervals for the age of undated moraines are computed from the mean and the variance of previous age distributions. Finally, to reduce error estimates, measurements

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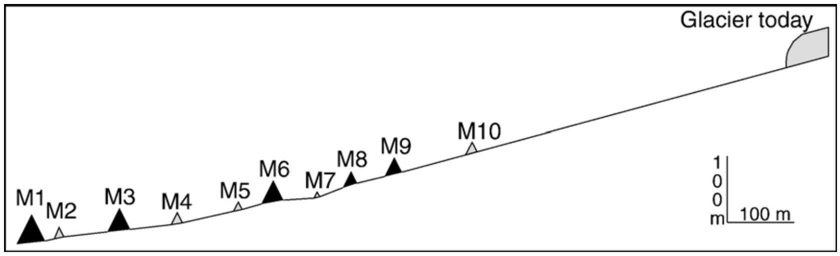

Figure 2. Morphostratigraphy of the 10 main moraines of the Bolivian glacier forelands. Black triangles represent the biggest moraines that attest to a glacier advance or a long standstill; grey triangles represent only a short halt of the snout during a glacier recession. The distance between the moraines and differences in altitude are averaged for the 15 glacier forelands considered in this study. The height of the moraine does not match the vertical scale.

corresponding to dated and undated surfaces are collected in the same data set and analysed together.

Reconstruction of glacier parameters and climatic interpretation

Glacier areas corresponding to the moraine contours were reconstructed for each glacier. Stereo-photogrammetric reconstructions were made for the AD 1940–1997 period (Rabatel et al., 2006). The ELA was determined on each glacier and each morainic stage using the accumulation area ratio (AAR) method (Gross et al., 1978).

Glacier LIA volumes were reconstructed by contour line interpolation based on the moraine height and the bedrock morphology. For the 20th century, volume variations were computed using photogrammetric reconstructions of the Charquini glaciers only (Rabatel et al., 2006). Then, as the moraines were dated and the date of aerial photographs was known, it was possible to calculate the mean annual mass balance for each period (Rabatel, 2005; Rabatel et al., 2006).

To interpret glacier variations as a paleoclimatic proxy requires that glacier–atmosphere interactions are known, particularly variables such as mass balance and ELA, and the climatic parameters that govern their fluctuations. A possible modelling approach consists in deriving temperature and precipitation from ELA fluctuations using Kaser's (2001) model. Details of this approach can be found in this paper or in Rabatel (2005, chapters 3.4.1 and 3.4.2.) where the variables and constants used are fully described. We briefly mention here that it consists in translating variations of ELA into variations of accumulation amounts, temperature, radiative balance or any combination of these parameters according to Eq. (2):

$$\frac{\partial c}{\partial z}\Delta_{\mathrm{ELA}} + \Delta c = F_{\tau}\left\{\delta[\mathrm{G}(1-\alpha)] + C_{\mathrm{S}}\left(\frac{\partial T_{\mathrm{a}}}{\partial z}\Delta_{\mathrm{ELA}} + \Delta T_{\mathrm{a}}\right) + C_{\mathrm{R}}\Delta T_{\mathrm{a}}\right\} \tag{2}$$

where, F, characterizing the contribution of melting and sublimation in ablation processes is given by:

$$F = \frac{1-f}{L_{\mathrm{M}}} + \frac{f}{L_{\mathrm{S}}} \tag{3}$$

and:

$$f = \frac{Q_{\mathrm{L}}}{Q_{\mathrm{M}} + Q_{\mathrm{L}}} \tag{4}$$

with, Δ_{ELA} the ELA variation between two glacier stages; $\partial c/\partial z = 0.0003$ m m^{-1} and $\partial T_a/\partial z = -0.006$ °C m^{-1} are respectively the precipitation and air temperature gradients; Δc (m m^{-1}) and ΔT_{a} (°C) represent accumulation and temperature variations between two considered glacier stages; $C_{\mathrm{S}} = 1{,}7$ MJ m^{-2} day^{-1} K^{-1} and $C_{\mathrm{R}} = 0.28$ MJ m^{-2} day^{-1} K^{-1} are heat transfer coefficients; $G(1-\alpha)$ represents the net radiation; L_{M} e$=0.334$ MJ kg^{-1} and $L_{\mathrm{S}} = 2.835$ MJ kg^{-1} are the latent heat for melting and sublimation, respectively; and Q_{L} and Q_{M} are the heat fluxes for sublimation and melting, respectively.

We also used the mass-balance sensitivity analysis proposed by Hastenrath and Ames (1995), which consists of interpreting mass-balance variations in terms of energy modulation. Assuming that all the energy available at the glacier surface is used for melting, the possible variations of climatic parameters (cloudiness, air temperature and relative humidity) that can produce such an energy modulation can be deduced independently (see Hastenrath and Ames, 1995 for more details).

Results

LIA moraine chronology

Figure 2 presents the typical succession of moraines found on glacier forelands. Geomorphic criteria enabled us to distinguish: 1) prominent moraines—several meters high with a steep outer slope—that are caused by glaciers advancing or remaining in the same position for several years. In some cases these moraines have removed small ridges; and 2) small and blunted moraines, which indicate short breaks in the glacier recession.

We identified 10 main morainic ridges (numbered upstream from M1 to M10) in each foreland of the 15 glaciers sampled. The succession and the morphology of all the moraines are similar (Figs. 1 and 2). The typical moraine sequence of the proglacial margins of the Bolivian Eastern Cordillera is consistent with that previously identified in the Charquini massif (Rabatel et al., 2005).

Table 2
Lichenometric measurements from the 10 main moraines of the Bolivian Eastern Cordillera glaciers used in this study

	Ichu Kota glaciers				Charquini glaciers										Huayna Potosi glaciers				Quimsa Cruz glaciers							
	Jankhu Uyu		Wila L.		Southern		South-E.		North-E.		Northern		Western		HP West		Zongo		Malla C.		San Enrique		Jankho L.		Yaypuri	
Moraine	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
1	35–40	30	38–40	10	32–40	31	35–40	30	37–40	20	36–41	20	35–41	28	37–40	14	35–41	25	36–41	30	36–41	30	35–41	20	36–40	20
2	33–35	10			33–35	10			33–36	20	32–35	20	32–36	20	33–36	15			32–36	30	32–36	30			33–38	20
3	29–32	40	29–32	20	29–35	15	29–32	26	29–33	20	28–31	25	28–32	30	29–31	20	29–32	25	26–33	30	26–33	30	28–33	30	28–34	15
4	26–30	11	26–29	15	26–28	15	27–30	26	27–29	22	27–29	30	25–29	30	25–30	24	26–29	25	26–31	40	26–31	40			28–30	20
5	23–28	35	22–27	20	20–25	10			26–29	20	25–28	25	26–29	30	26–28	20	25–28	25	23–28	20	23–28	20			26–29	20
6	18–24	25			19–25	30	23–25	30	23–25	20	23–25	25	22–26	35	23–25	20	23–25	20	21–27	40	21–27	40	21–29	30	23–26	20
7	17–22	20			16–22	15	20–22	10	20–22	20	20–22	20	20–23	30			19–22	20	20–23	10	18–22	20			21–23	20
8					16–19	26	16–19	30	16–19	20	17–19	30	16–18	30	16–19	20	16–19	20	15–19	20	15–19	20	16–22	30	15–20	20
9	14–18	15			13–16	20	14–17	30	15–17	20	14–16	30	14–17	30	14–16	20	14–16	20	14–16	20	15–17	10	15–18	30	15–18	20
10	9–12	20	10–12	20	9–12	40	10–13	30	10–13	20	9–12	30	9–12	30			9–13	20	10–12	15			10–12	30	10–12	20

For each glacier, column (1) presents the diameter range (in mm) of the biggest lichen measured on a block, and column (2) presents the number of blocks sampled on each moraine.

Lichenometric measurements were made on all these morainic systems except in the Condoriri area, whose metamorphic rocks of sedimentary origin prevent *Rhizocarpon sp.* from growing. Each morainic stage presented the same lichenometric pattern, that is equivalent maximum diameters (Table 2). The chronology of the 13 glaciers evolution is shown in Table 3 and Figure 3. Dates are very consistent from one glacier to another and confirm the chronology of glaciers in the Charquini massif (Rabatel et al., 2005). We thus propose this chronology of glacier fluctuations during the LIA as a reference for the Bolivian Andes:

–The M1 moraine (dating from AD 1657±24 to 1686±26) attests that glaciers reached their LIA maximum during the second half of the 17th century. Interstratified pieces of peat found in the M1 moraine of the Southern Charquini Glacier were dated 860–730 cal yr BP (Gif-11869).
–After this maximum, glaciers deposited the very close M2 moraine dating from AD 1700±14 to 1706±35 during a short standstill.
–M3 dates from the AD 1732±22 to 1740±16 interval and marks a clear glacier advance during the second quarter of the 18th century. In several places this moraine partially removed the ridge deposited during the M2 stage.
–In the second half of the 18th century, short standstills left two small ridges labelled M4 and M5.
–The next marked glacier advance dates from the turn of the 18th–19th centuries when the M6 moraine (AD 1791±18 to 1811±19) was deposited.
–During the course of the 19th century, glaciers formed three moraines: M7, M8 and M9. The shape of the last, M9, proves that glaciers advanced moderately during the 1860s.
–Finally, the last glacier standstill determined from a moraine (M10) is dated about AD 1910.

Changes in glacier surface area, ELA and mass balance

Changes in glacier surface area from the 17th to the late 20th century are presented in Table 4 and plotted in Figure 4. Over the whole period, glaciers lost an average of 59±16% of their area, with extreme values ranging from 29% to 87%. Glacier recession was not homogenous over time but proceeded in five steps:

1) The M1–M3 period [AD 1665±16; 1735±6]: during this 60-year period, glaciers changed minimally and only retreated at a rate of around 0.08×10^{-2} km² yr^{-1}.
2) The M3–M6 period [AD 1735±6; 1800±14]: glaciers shrunk faster at a rate of 0.33×10^{-2} km² yr^{-1}; this recession was only interrupted by the glacier advance that resulted in M6.
3) The M6–M9 period [AD 1800±14; 1870±8]: after the advance in the early 19th century, glaciers lost ground throughout the 19th century at a rate close to 0.29×10^{-2} km² yr^{-1}.
4) The M9–M10 period [AD 1870±8; 1909±4]: during the late 19th and early 20th century, glacier retreat rates were

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Table 3
Moraine dating by lichenometry with the associated error (years AD) for the LIA stages

Moraine	Ichu Kota glaciers		Charquini glaciers					Huayna Potosi glaciers		Quimsa Cruz glaciers			
	Jankhu Uyu	Wila L.	Southern	South-E.	North-E.	Northern	Western	HP West	Zongo	Malla C.	San E.	Jankho L.	Yaypuri
1	1658±22	1662±23	1686±26	1664±21	1662±18	1663±24	1663±23	1657±24	1680±28	1665±25	1665±25	1660±27	1659±23
2	1704±22		1703±25		1700±16	1706±35	1700±14	1704±18		1702±20	1702±20		1703±23
3	1734±26	1732±22	1734±21	1736±12	1740±16	1740±14	1739±17	1734±18	1732±16	1736±28	1736±28	1735±37	1735±20
4	1756±20	1755±19	1765±17	1755±12	1758±25	1755±16	1755±13	1758±15	1766±17	1756±30	1756±30		1749±18
5	1775±17	1775±21			1767±12	1769±12	1763±13	1783±9	1781±15	1770±14	1770±14		1768±14
6	1805±19		1808±14	1792±19	1794±17	1794±14	1791±18	1805±15	1811±19	1799±26	1799±26	1804±20	1795±21
7	1817±16		1825±17	1819±18	1817±19	1817±14	1815±14		1822±18	1816±18	1813±19		1815±29
8			1843±16	1849±15	1848±14	1847±18	1852±14	1857±17	1852±14	1849±17	1845±25	1854±22	1844±28
9	1869±12		1871±23	1868±22	1864±16	1870±19	1873±25	1876±16	1871±16	1864±22	1865±25	1873±23	1871±23
10	1908±10	1909±12	1912±17	1909±15	1905±12	1910±19	1907±19		1911±9	1908±8		1910±14	1909±7

Dating is absent when there were not enough blocks on moraines to allow sufficient lichenometric measurements.

25% higher than during the previous period (0.39×10^{-2} km² yr^{-1}).

5) The M10-1997 period: over the 20th century, the mean recession was slower than during the short M9-M10 period, but it remained fast, with a rate close to 0.30×10^{-2} km² yr^{-1}.

Based on this chronology, we can assume that in this part of the Andes, the LIA maximum occurred during the second half of the 17th century. Glaciers remained very extensive until about AD 1735. During the first half of the 19th century, glaciers continued to retreat, though at a reduced rate. The acceleration in the rate of retreat between stages M9 and M10 of all the glaciers allows us to affirm that, in this region, the LIA ended between 1870 and 1910.

Glacier equilibrium lines reconstructed using the AAR method reveal a mean altitude of 4965±95 m asl for the LIA maximum (Table 5). Using the same method, the average ELA found for the late 20th century is 5098±85 m asl. However, this value does not match the ELA_0 measured on the Zongo glacier for the AD 1991–2005 period (5250 m asl), which is about 150 m higher. This 150 m discrepancy between the "AAR-derived ELA" and the measured ELA is assumed to represent the current imbalance of glaciers in this part of the Andes. Assuming that all the glaciers used in this study are similarly unbalanced and that their current ELA_0 is the same as on Zongo glacier, we can state that the ELA has risen by 285±50 m since the LIA maximum. Further, it can be stated that 63% of this rise in elevation took place between the late 19th and the late 20th century.

Figure 5 shows the mass balance reconstructed for two periods, first during the M1–M9 period (i.e., the LIA maximum and the late 19th century, the period considered as the classical LIA worldwide), and second for the M9 period of the late 20th century. During the latter period, glaciers shrank three times more rapidly than during the former. The reconstructed ELAs confirm that the period from the late 19th to the early 20th century was a transitional period when glacier recession accelerated; indeed, the mean ELA rose at a rate of 0.74 m yr^{-1} during the M9–M10 period (3 times the M1–M9 rate). This change in the rate of glacier recession suggests significant changes in climate conditions from about AD 1870 onwards.

Discussion

Were glacier fluctuations in Bolivia during LIA synchronous with, and of the same magnitude as those in other massifs in the tropics and in the rest of the world?

The LIA maximum occurred in Bolivia during the second half of the 17th century. This result is in good agreement with results of Solomina et al. (2007) and Jomelli et al. (in press) in the Cordillera Blanca (see above). This evidence enables us to assume that the LIA maximum in the Central Andes coincided with that of many glaciers in mid-latitude regions.

The presence of peat in the M1 moraine of the Southern Charquini Glacier revealed that the glacier advanced on a substrate (a peat bog) formed well before the LIA and not removed by any glacier prior to the late 17th century. The lack of major glacier advances prior to the last four centuries is in agreement with ^{14}C dates obtained by Gouze et al. (1986) from the top layer of a peat bog covered by M1 in the Ichu Kota Valley (670–280 cal yr

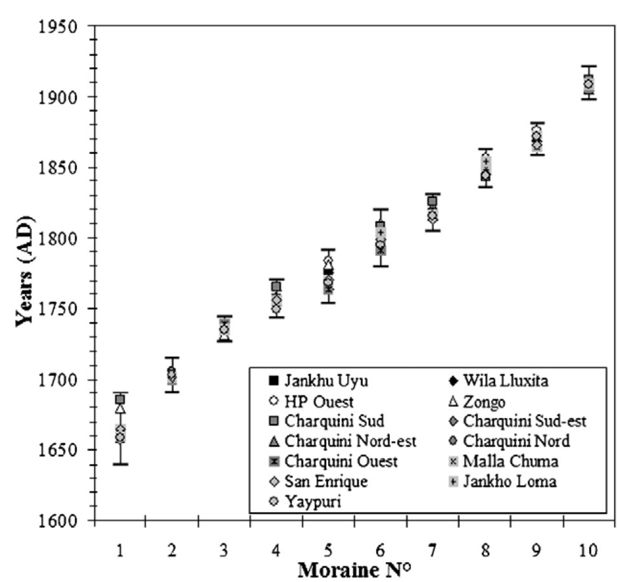

Figure 3. Lichenometric dating for each one of the 10 main morainic stages for 13 glacier forelands. 95% confidence intervals are plotted.

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Table 4
Glacier surface area (km²) reconstructed from the moraines for the LIA and by photogrammetry from 1940

		Ichu Kota glaciers		Charquini glaciers					Huayna potosi glaciers		Condoriri glaciers		Mean	σ
		Jankhu Uyu	Wila L.	Southern	South-E.	North-E.	Northern	Western	HP West	Zongo	Condoriri	Tarija		
Moraine	1	0.708	1.004	1.220	1.413	1.042	1.056	0.838	3.818	3.319	0.779	3.694		
	2	0.702	1.001	1.163	1.403	1.016	1.040	0.784	3.761	3.276	0.772	3.627		
	3	0.682	0.997	1.156	1.378	0.990	1.016	0.698	3.704	3.234	0.763	3.590		
	4	0.632	0.847	1.110	1.345	0.957	0.960	0.660	3.554	3.013	0.749	3.434		
	5	0.618	0.785	1.076	1.243	0.919	0.912	0.621	3.321	2.991	0.745	3.299		
	6	0.614	0.769	1.037	1.222	0.898	0.884	0.578	3.177	2.952	0.740	3.164		
	7	0.591	0.662	0.983	1.210	0.851	0.859	0.475	3.003	2.850	0.695	3.009		
	8	0.587	0.640	0.947	1.199	0.820	0.852	0.462	2.872	2.816	0.692	2.854		
	9	0.531	0.593	0.852	1.180	0.783	0.834	0.411	2.782	2.738	0.685	2.764		
	10	0.437	0.458	0.783	0.941	0.627	0.661	0.315	2.640	2.620	0.658	2.353		
Aerial photographs	1940			0.747	0.837	0.573	0.531	0.267						
	1956			0.708	0.790	0.508	0.420	0.246	2.425	2.479				
	1963			0.685	0.732	0.509	0.388	0.217						
	1974			0.650	0.690	0.483	0.352	0.185						
	1983			0.595	0.633	0.444	0.311	0.141	2.156	2.360	0.444	1.553		
	1997	0.335	0.329	0.493	0.521	0.359	0.232	0.108						
Surface variation (% of the LIA maximum surface area)	M1-M3	−4	−1	−5	−2	−5	−4	−17	−3	−3	−2	−3	−4	4
	M3-M6	−10	−23	−10	−11	−9	−12	−14	−14	−8	−3	−12	−11	5
	M6-M9	−12	−18	−15	−3	−11	−5	−20	−10	−6	−7	−11	−11	5
	M9-M10	−13	−13	−6	−17	−15	−16	−11	−4	−4	−3	−11	−10	5
	M10-late 20th	−14	−13	−24	−30	−26	−41	−25	−13	−8	−27	−22	−22	9
	M1-M9	−25	−41	−30	−16	−25	−21	−51	−27	−18	−12	−25	−26	11
	M9-late 20th	−14	−13	−24	−30	−26	−41	−25	−13	−8	−27	−22	−22	9
	M1-late 20th	−53	−67	−60	−63	−66	−78	−87	−44	−29	−43	−58	−59	16

BP). This leads to the conclusion that if glaciers advanced in these tropical mountains during the 13–14th centuries, as documented for the northern mid-latitudes (Grove, 1988), they did not extend beyond the position they reached during the 17th century.

Estimated loss in surface area by the Bolivian glaciers between the LIA maximum and the late 20th century is in agreement with losses estimated for other glaciers in the intertropical zone: 80% for Chacaltaya glacier, Bolivia (Ramirez et al., 2001), 53% for Yanamarey glacier, Peru (Hastenrath and Ames, 1995), 80% for glaciers of the Pico Bolivar, Venezuela (Schubert, 1972), 85% for Carstensz and Meren glaciers, Indonesia (Peterson and Peterson, 1994).

Furthermore, the significant retreat of Bolivian glaciers observed during the late 19th – early 20th century agrees with evidence from historical sources in Peru and Ecuador, where the glaciers retreat was reported to accelerate after AD 1860–1870 (see above).

Finally, the total ELA rise of 285±50 m since the LIA maximum found for the Bolivian glaciers is close to the 300 m reported for the Ecuadorian Andes by Francou (2004) on the basis of documentary information or results obtained in Cordillera Blanca (Jomelli et al., in press).

Outside the Central Andes, it should be noted that the maximum and the main phases of the LIA glacier evolution in Bolivia are in agreement with those of the well-documented glaciers in mid-latitude mountain ranges. Indeed, Figure 6 shows that the glacier maximum in Bolivia (M1–M3) is quite similar to glacier expansions observed in the European Alps in the mid/late 17th century (Le Roy Ladurie, 2004) and during the first half of the 18th century in Scandinavian mountain ranges (Nesje and Dahl, 2000), the Canadian Rockies (Luckman, 2000), the Patagonian Andes (Luckman and Villalba, 2001) and the Southern Alps of New Zealand (Winkler, 2004). Just before the second half of the 18th century, glaciers progressively retreated in Bolivia, as was the case of many glaciers in the Alps (Zumbühl and Holzhauser, 1988) and in Scandinavia (Nesje and Dahl, 2003).

In Bolivia, the recession slowed down during the period from the late 18th–early 19th century until about AD 1870 and even halted for a short period at the turn of the 18th–19th century when the M6 moraine was formed. By contrast, in the Alps, Canada and other locations in the Northern Hemisphere, many glaciers advanced significantly between AD 1810 and 1850 and, in some locations, as much as or even more than the former advance dated from the 17th–18th centuries.

The trend to Bolivian glacier recession accelerated after AD 1870 up to the beginning of the 20th century. This acceleration in the recession coincides with the decrease in surface area of many glaciers worldwide, particularly in the Alps (Grove, 1988).

Climatic inferences

The simultaneity of glacier advances during the LIA with solar activity minima

The timing of glacier maximum in Bolivia highlights the striking coincidence between the glacier expansion in this region

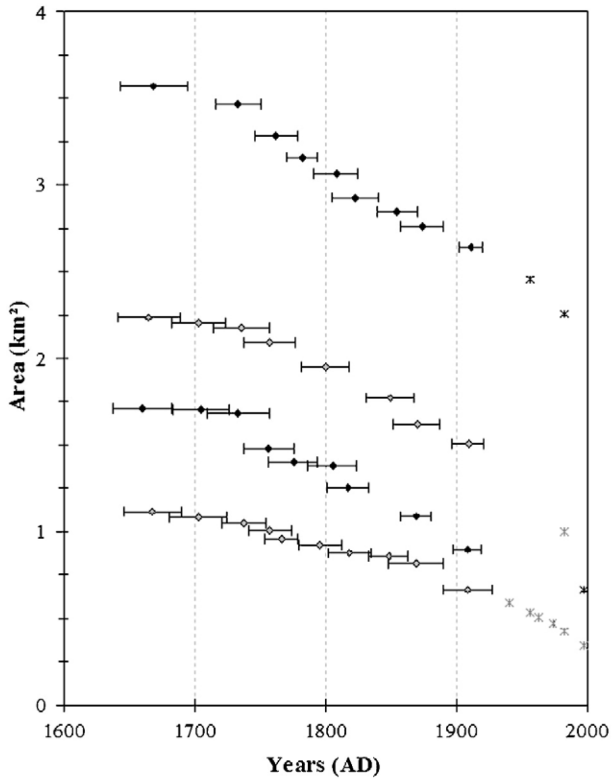

Figure 4. Changes in surface areas of glaciers since their LIA maximum at different sites (From top to bottom: Huayna Potosi, Condoriri, Ichu Kota and Charquini). Surface areas were reconstructed on the basis of moraines up until the early 20th century (diamond-shaped), then by photogrammetric restitution (crosses). Errors bars represent uncertainties in moraine dating. For Huayna Potosi, Charquini and Ichu Kota massifs, dates correspond to the average lichenometric dating of the morainic stages for glaciers of each massif. For the Condoriri area, as lichenometric measurements were not possible (the required species of lichen does not grow there), the dates correspond to the mean of the dating for all the other glaciers.

of the tropics and the decrease in solar irradiance: the so-called "Maunder minimum" (AD 1645–1715) during which irradiance might have decreased by around 0.24% (Lean and Rind, 1998) and could have resulted in an atmospheric cooling of 1 °C worldwide (Rind et al., 2004). This coincidence could strengthen arguments linking solar activity and glaciers expansion worldwide (Eddy, 1976). In the tropics, the link between the two events could be more obvious than elsewhere, since all recent studies based on energy balance pinpointed the role of the radiative balance in ablation rates of glaciers (Wagnon et al., 1999).

At the time of the following less pronounced solar irradiance minimum, the so-called "Dalton minimum" in AD 1783–1830 (Usoskin et al., 2002), we observed a clear break in the glacier recession in the Bolivian Andes. Interestingly, the advance marked by M6 [AD 1791 ± 18; 1811 ± 19] preceded the Tambora eruption (AD 1815). The Tambora veil is often cited as a possible cause for the second wave of glacier expansion after 1815 (Free and Robock, 1999). If the accuracy of our LIA chronology conforms with error bars in Table 3 and Figure 3, the glacier advance in the tropical Andes might have preceded the effect of the Tambora veil and consequently be mainly due to solar forcing.

We already mentioned the hypothesis of the influence of solar forcing on tropical glaciers (Rabatel et al., 2005) based on the chronology of the Charquini glaciers and evidence provided by Polissar et al. (2006) strengthens this hypothesis.

Climatic conditions at the LIA maximum

We above mentioned that tropical glaciers are very sensitive to precipitation. In addition to increasing accumulation of snow above the ELA, snowfalls have a strong influence on the net radiative balance in the ablation zone via the albedo. Indeed, frequent and intense snowfalls during the wet season are necessary to reduce ablation and to lead to positive mass balances at an annual scale (Wagnon et al., 2001; Francou et al., 2003). Thus, in the light of the new chronological evidence, we can affirm that climatic conditions before the second half of the 17th century maximum had to be humid and cold to trigger such a pronounced glacier advance.

We used Hastenrath and Ames' (1995) mass-balance sensitivity analysis and Kaser's (2001) model to interpret the glacier fluctuations and tested several scenarios by changing only one parameter, namely accumulation, cloudiness, temperature, humidity or radiative balance, or by changing all the parameters simultaneously. We estimated that to increase mass

Table 5
Equilibrium-Line Altitude reconstructed using the AAR method based on the moraine for the main stages of the LIA and on aerial photographs for the 20th century

		Ichu Kota glaciers		Charquini glaciers					Huayna Potosi glaciers		Condoriri glaciers	
		Jankhu Uyu	Wila L.	Southern	South-E.	North-E.	Northern	Western	HP West	Zongo	Condoriri	Tarija
Moraine	1	5100	4950	4930	4815	4870	4990	4910	5080	5090	4980	4900
	3	5120	4960	4935	4820	4885	4995	4915	5090	5100	4990	4915
	6	5130	4970	4965	4820	4910	5010	4930	5110	5140	5000	4920
	8			4985	4825	4920	5020	4950				
	9	5170	5000	4995	4830	4940	5030	4965	5120	5150	5010	4940
	10	5200	5040	5025	4905	4950	5070	4980	5130	5160	5030	4980
Aerial photographs	1940			5030	4925	4965	5110	4990				
	1956			5035	4935	4985	5120	5000	5145	5180		
	1963			5040	4940	5000	5130	5010				
	1974			5055	4945	5005	5140	5015				
	1983			5075	4950	5010	5145	5020	5170	5210	5050	5020
	1997	5230	5090	5095	4960	5060	5165	5025				

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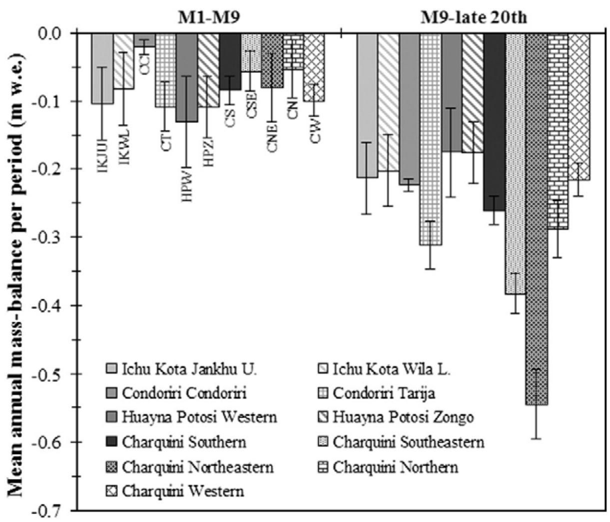

Figure 5. Mean mass balance per period for 11 glaciers in the Bolivian Cordillera Real, reconstructed on the basis of the M1 and M9 moraines and 1983 and 1997 photogrammetric restitutions. Uncertainty bars represent the margin of error of the lichenometric dating and the reconstruction of glacier volume.

balance and induce the pronounced glacier advance of the 17th century, precipitation and cloudiness had to increase by 20–30% and 0.1–0.2, respectively compared to present conditions. Independently, temperature had to decrease by 1.1–1.2 °C.

Nowadays such anomalies are observed during the cold ENSO phases (La Niña) (Wagnon et al., 2001; Francou et al., 2003) and lead to an excess of mass of 200–500 mm w. e. yr^{-1} on the Zongo glacier. These conditions would have to occur for several decades to generate the glacier advances observed during the LIA. As mentioned above, Thompson et al. (1986) defined the LIA limits between AD 1500 and 1900. Reconstruction of precipitation from ice core evidence enabled these authors to identify an initial wet period from AD 1500 to 1720, with accumulation rates 25% higher than those during previous and subsequent periods. Furthermore, Liu et al. (2005) demonstrated on the basis of a high-resolution ice core pollen record from the Sajama Ice Cap (Bolivia) that the AD 1500–1700 period was characterised by wet conditions. High accumulation rates found on the Quelccaya ice cap (14°S), associated with increased precipitation, and evidence from the pollen record are consistent with those of extensive glaciers in Northern Bolivia (16°S) and Northern Peru (10°S) during the same period. These high precipitation rates could be the consequence of a long pattern of ocean-atmosphere circulation during the high phase of the Southern Oscillation (Niña-like conditions) that generates increased precipitation in the Central Andes (Hastenrath et al., 2004).

Interpreting the glacier retreat during LIA

Glaciers began to recede in the Bolivian Andes after AD 1740. The glacier retreat was moderate but continuous until about AD 1870. In this region, no evidence has yet been discovered that temperatures increased in the mid-18th century during the summer, as it did in Europe and other parts of the Northern Hemisphere (e.g., Chuine et al., 2004; Moberg et al., 2005). Consequently, we assume that glacier changes after AD 1740 were caused by continuous dry conditions. On the basis of the paleoclimatic interpretation of the ELA and mass-balance reconstruction (see Figure 5) and using Kaser and Hastenrath and Ames models, we calculated that such dry conditions resulted in a decrease in accumulation rates on glaciers of about 20%. The little information available on the LIA in the tropical Andes coming from other proxies is consistent with a drier

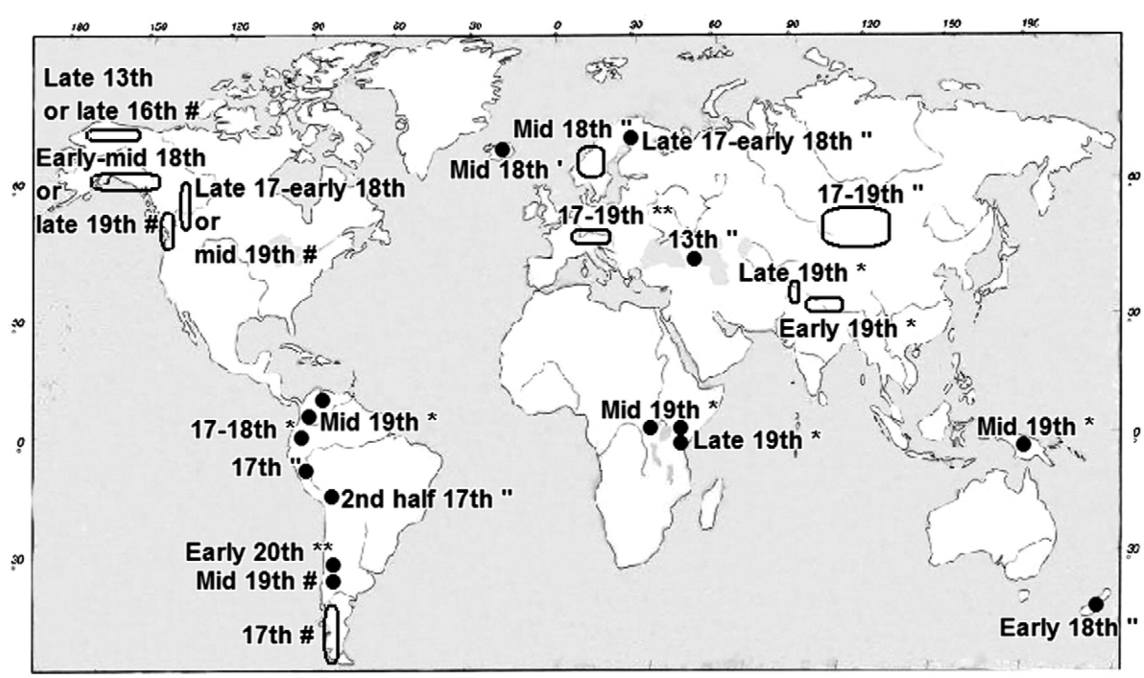

Figure 6. Dating of the LIA maximum throughout the world. Sources are quoted in the text. This dating was based on different methods: "lichenometry, **historical documents, #dendrochronology, 'tephrochronology and ∗presumed dates.

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climate in the second part of the LIA (i.e., ~AD 1740–1870). On the Quelccaya ice cap, according to Thompson et al. (1985), we can infer a decrease of about 20% in precipitation from AD 1720 to 1880. Also on the Sajama ice cap, Liu et al. (2005) have shown that dry conditions prevailed from AD 1700 to 1880.

During the late 19th–early 20th century, the accelerated glacier recession observed in the Central Andes is not consistent with temperatures measured at world scale, which did not increase significantly before the first half of the 20th century (IPCC, 2001). The significant rise in the ELA can be thus interpreted in terms of precipitation variations only. Such variations could have been characterized by a decrease of 15–20% compared with the present. Using a network of weather stations distributed throughout the intertropical zone, Kraus (1955) identified an abrupt decrease in precipitation during the period AD 1870–1900 and attributed the reduction to a shortening of the rainy season. Other evidence was provided by paleohydrological reconstructions from lakes of the Peruvian–Bolivian Altiplano (Valero-Garces et al., 2003; Chepstow-Lusty et al., 2003). These authors showed that the level of several lakes was low between AD 1880 and 1905, which implies low precipitation on the Altiplano. The precipitation deficit could be associated with more frequent and intense warm phases of the ENSO. This is in agreement with results of Torrence and Webster (1999), who used SST in the Niño-3 zone (5°S–5°N, 90°–150°W) and monthly precipitation measurements in India (both available since 1871) and concluded that the period from AD 1875 to 1920 was characterized by a high frequency of El Niño events. Consequently, a succession of El Niño events could have triggered the LIA ending in the Central Andes.

Interpretation of the glacier retreat in the 20th century

Precipitation in La Paz has not displayed any significant trends over the last 100 years (Gioda et al., 2004). Based on this information, the ELA rise of 55±27 m and the annual mass balance deficit of 0.46 m w.e. yr^{-1} (means of all studied glaciers), computed for the period between ca. AD 1910 (M10) and 1997, cannot be interpreted in terms of changes in precipitation. Glacier retreat in the 20th century was rather a consequence of increases in temperature and humidity. The sensitivity analysis of glaciers gives an increase in temperature and humidity of 0.7–1 °C and 0.25 $g \cdot kg^{-1}$, respectively, or any combination of these two parameters.

The increase in temperature reconstructed from glacier fluctuations is in good agreement with results of Vuille and Bradley (2000), who suggest an increase of 0.1 °C/decade since 1939 on the basis of temperature series recorded at weather stations in the tropical Andes. Vuille et al. (2003) also assume that atmospheric humidity increased in the tropical Andes, but uncertainties persist concerning suggested rates due to the lack of reliable long-term measurements.

Conclusion

Moraines of 15 glaciers in the Bolivian Eastern Cordillera were dated by lichenometry enabling us to present a detailed chronology of glacier evolution during the LIA. A clear glacier maximum is apparent in the second half of the 17th century and in the first decades of the 18th century. This coincides with the main glacier expansions observed in other mountain regions. Subsequently, the continuous retreat of glaciers in Bolivia throughout the 18th and the 19th centuries is more unusual and was not observed on mid-latitude glaciers. Acceleration of glacier recession in the late 19th century put an end to the LIA in the Andes. Climatic interpretation of glacier fluctuations allows us to assume that the LIA maximum in the Bolivian Andes was the consequence of enhanced precipitation (20–30% higher than the current mean) and reduced temperature (between 1.1 and 1.2°C lower than the current mean). The Maunder solar irradiance minimum is a possible cause of this temperature decrease. After this maximum, glaciers continued to retreat until the last decades of the 19th century due to a very significant drop in precipitation (~20%). Glacier recession in the 20th century is thought to be due to a temperature increase of 0.7–1 °C accompanied by a probable increase in atmospheric humidity.

If confirmed by similar analysis at other sites in the tropical Andes, this chronology would prove that glacier response in the tropics during the LIA was mainly driven by a combination of solar energy modulation and regional changes in precipitation. The next step will be to model the relation between climate and glaciers in this zone. Now that we have a detailed chronology of glacier fluctuations, only a robust model based on energy balance measurements will allow the question of the climate reconstruction in the Central Andes lasting recent centuries to be addressed. A reconstruction of this type, based on glacier evidence, will then have to be compared with reconstructions based on other proxies such as ice cores, tree rings and lake sediments.

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