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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.

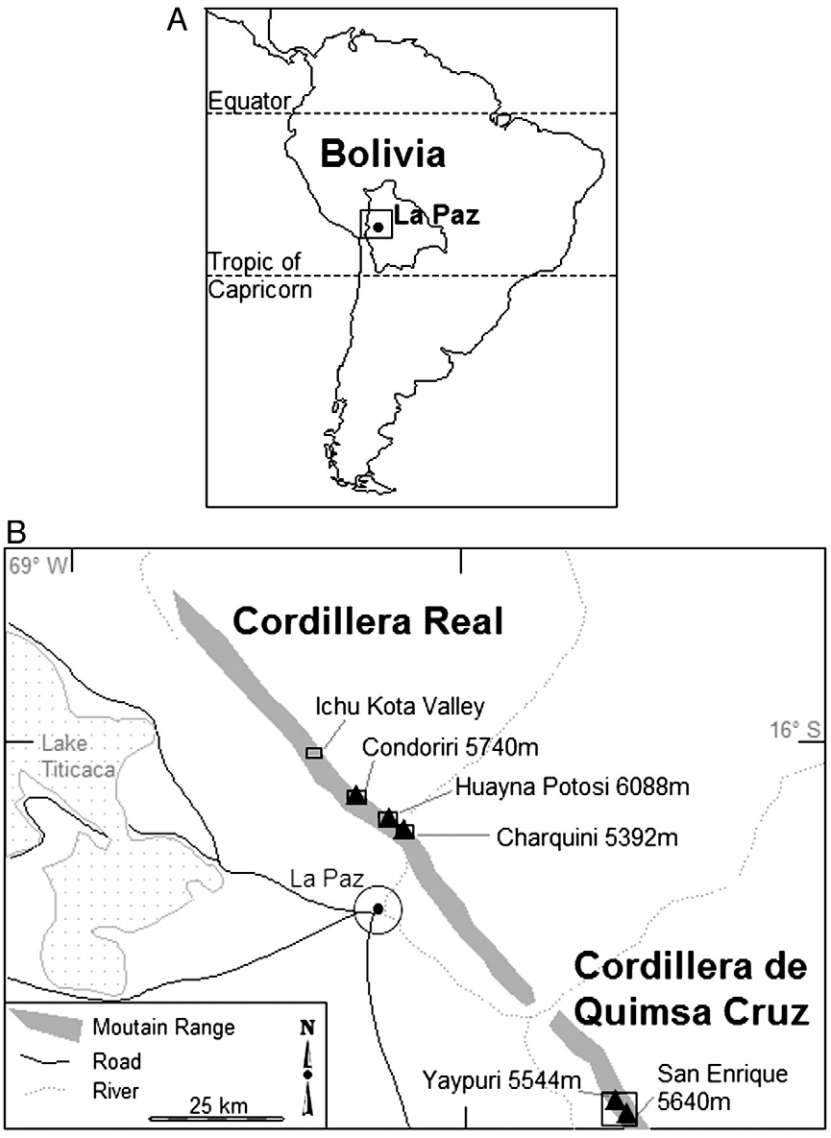

Figure 1. Study area: General map (A and B), Charquini Massif (C), Huayna Potosi Massif (D), Condoriri Massif (E), Ichu Kota Valley (F), Quimsa Cruz Massif (G). Although 10 moraines were found on each glacier foreland, only the five biggest (M1, M3, M6, M8 and M9) are shown here.