doi:10.1038/nature10150

Irregular tropical glacier retreat over the Holocene epoch driven by progressive warming

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The causes and timing of tropical glacier fluctuations during the Holocene epoch (10,000 years ago to present) are poorly understood. Yet constraining their sensitivity to changes in climate[1] is important, as these glaciers are both sensitive indicators of climate change and serve as water reservoirs for highland regions[2]. Studies have so far documented extra-tropical glacier fluctuations[3,4], but in the tropics, glacier–climate relationships are insufficiently understood. Here we present a ^{10}Be chronology for the past 11,000 years (11 kyr), using 57 moraines from the Bolivian Telata glacier (in the Cordillera Real mountain range). This chronology indicates that Telata glacier retreated irregularly. A rapid and strong melting from the maximum extent occurred from 10.8 ± 0.9 to 8.5 ± 0.4 kyr ago, followed by a slower retreat until the Little Ice Age, about 200 years ago. A dramatic increase in the rate of retreat occurred over the twentieth century. A glacier–climate model indicates that, relative to modern climate, annual mean temperature for the Telata glacier region was −3.3 ± 0.8 °C cooler at 11 kyr ago and remained −2.1 ± 0.8 °C cooler until the end of the Little Ice Age. We suggest that long-term warming of the eastern tropical Pacific and increased atmospheric temperature in response to enhanced austral summer insolation were the main drivers for the long-term Holocene retreat of glaciers in the southern tropics.

Accurate documentation of past glacier fluctuations in the tropics is of primary importance in understanding the climate processes and thresholds responsible for their mass balance variations. Recent papers[5–11] documenting Holocene deglaciation in the Andes on the basis of dated moraines and proglacial lake sediments show that glaciers were larger than today in the early and late Holocene. Even though these

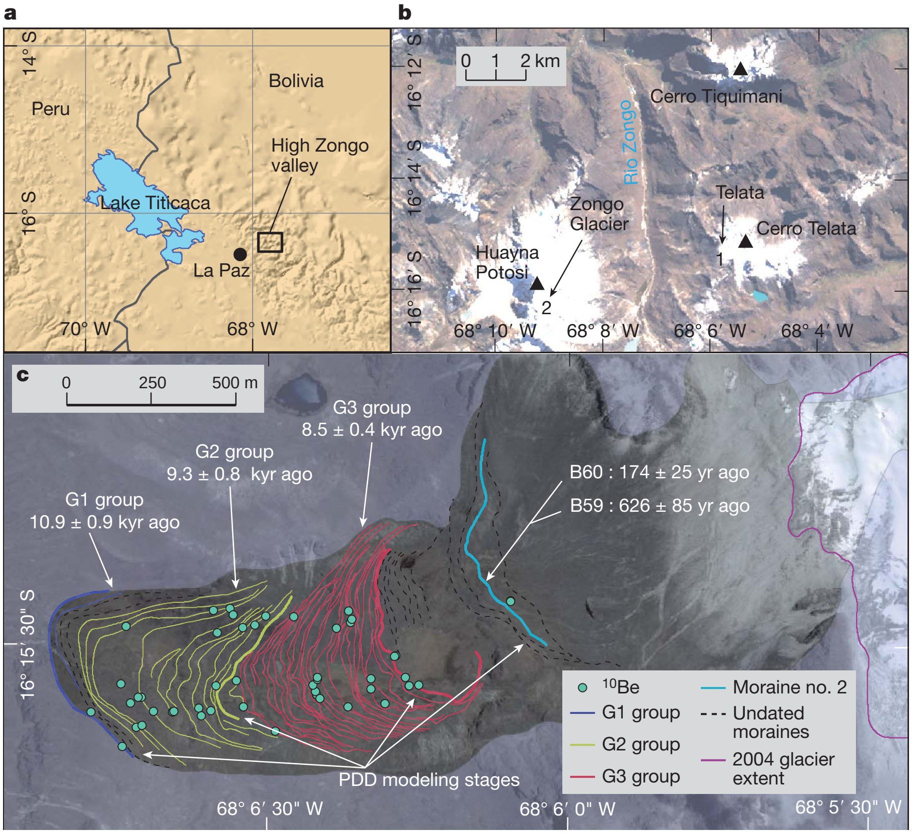

Figure 1 | Telata glacier and sampling sites. **a**, Location of the high Zongo valley. **b**, Local map showing the study sites: 1, the Telata glacier; 2, the location of the Zongo glacier; filled triangles, summits. **c**, Map of the Telata glacier, showing dated and undated Holocene moraines (see Supplementary Information sections 1 and 2, Supplementary Tables 1–5), the location of ^{10}Be sampling sites (green dots), the extent of the Telata glacier in 2004 and the moraines used to run the PDD model. Uncertainty associated with the age of each group accounts for analytical uncertainties only.

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studies give precious information, little attention has been paid so far to reconstructing glaciological parameters, such as glacier mass balance, which provide the direct link to regional- and global-scale climatic conditions and which allow the constraining of temperature/precipitation changes responsible for the observed glacier fluctuations over the past 11 kyr.

In Peru and Bolivia, several glaciers exhibit numerous moraines younger than the Last Glacial Maximum (Supplementary Table 1). Here, relying on a very well preserved and complete sequence of 57 successive moraines from the Telata glacier in the Bolivian Cordillera Real, we explore the issue of tropical glacier evolution and how glaciers responded to climatic changes during the Holocene (Fig. 1).

To allow a precise reconstruction of the palaeoglacier extents, we carefully mapped these 57 Telata moraines. Their chronology was established from ^{10}Be exposure age dating on 59 sampled boulders (Fig. 1; Supplementary Information section 1, Supplementary Figs 1–5, Supplementary Tables 1–5). In order to get enough replicates to better constrain the uncertainties, moraines were pooled into three groups (G1–G3; see Supplementary Information section 1). Analytical uncertainties on the entire set of ^{10}Be ages averaged 5.4 ± 5.7%.

The first group of moraines (G1) dated to 10.8 ± 0.9 kyr ago on the ^{10}Be chronology (that is, 10.8 ± 0.9 ^{10}Be kyr ago; two samples). These correspond to the late glacial outer moraine M57 with frontal termination located at 4,400 m above sea level (a.s.l.) and three younger ridges, all formed during retreat periods. Two samples collected on M57 and on M56 were viewed as outliers—on the basis of a χ^2 test reflecting post-depositional processes, and of isotope inheritance from previous exposure (Supplementary Figs 3 and 4, Supplementary Table 4)—and were therefore rejected. The second group of moraines (G2, M53–M40) was dated to 9.3 ± 0.8 ^{10}Be kyr ago on the basis of 24 ^{10}Be samples. Two outliers located on M53, and three others located on M51, M46 and M42, were rejected (post-depositional processes and inheritance from previous exposure). The third group (G3, M39–M11) was dated to around 8.5 ± 0.4 ^{10}Be kyr ago, on the basis of 21 ^{10}Be samples. One outlier on M39 and two others located on M26 and on M22 were rejected from the analysis (Supplementary Figs 3 and 4, Supplementary Table 4). These early Holocene moraine advances correlate well with ^{10}Be-dated moraines in the southern Andes[5–8], revealing a regional synchrony. The last two moraines were deposited about 626 ± 85 and 174 ± 25 years ago, synchronously with the Little Ice Age (LIA) moraines observed in the nearby Zongo valley[12,13]. However, to compare these mean ages with other chronological records, an additional 9% uncertainty (linked to the uncertainty on the production rate) has to be considered and added to the analytical uncertainties (Supplementary Information section 1).

Between M57 and the front created in 2004, the glacier retreated by about 2.9 km. This retreat was however irregular and occurred in three distinct steps. The distance between the late glacial (11 kyr ago) and the early Holocene (8.5 kyr ago) frontal moraines is about 1.1 km, which equates to a minimum loss of 37% of the total length during a relatively short period. By contrast, the distance between the 8.5-kyr-ago and LIA frontal moraines is about 0.4 km, corresponding to a minimum loss of 13% of the total length over a longer time interval covering most of the Holocene. Finally, in the recent past, since the last moraine was deposited about 200 years ago, the glacier has undergone a reduction of more than 30% of its initial length. Today, the Telata is about 500 m long with a total surface area of 0.137 km^2, compared to 0.89 km^2 200 years ago and 1.79 km^2 11 kyr before present.

These three phases of glacier retreat since 11 kyr ago may have been caused by different combinations of warming and/or decline in precipitation. To explore potential combinations of precipitation and temperature changes (and resulting local climatic conditions) that are consistent with the extents of the Telata glacier, we applied an improved positive degree day (PDD) model[14] (see Methods) calibrated with measurements made on the nearby Zongo glacier (Fig. 1). We applied this model for three distinct climatic periods: (1) during deglaciation, 11 kyr ago, (2) the early Holocene (9.3 and 8.5 kyr ago), and (3) during the LIA (Supplementary Information sections 1 and 2, Supplementary Table 7). This model integrates the effects of solar radiation, accumulation and albedo through changes in glacier surface characteristics[14]. Indeed, energy balance measurements in Bolivia show that albedo is the main controlling factor for glacier ablation[15–17]. Although the model treats several physical processes in a simplified way, analyses in the Zongo watershed show that the model yields accurate results at annual and longer timescales[14]. In order to precisely reconstruct the palaeo-positions of the equilibrium-line altitude (ELA), the modelled mass balance law was projected on to the Telata topography by using an ice-flow model (Supplementary Text 1.3).

Using the present day climate data from Zongo, the model yields an ELA at 5,320 m a.s.l. (Fig. 2a), in good agreement with the currently observed ELA position of the Zongo glacier (Supplementary Information section 2). Model results for the late glacial moraine imply that 10.8 kyr ago, the ELA was at 4,800 m a.s.l, ~520 m below its current position. At 8.5 kyr ago and during the LIA (200 years ago), the ELA was located at 4,900 m a.s.l. and at 5,000 m a.s.l., respectively.

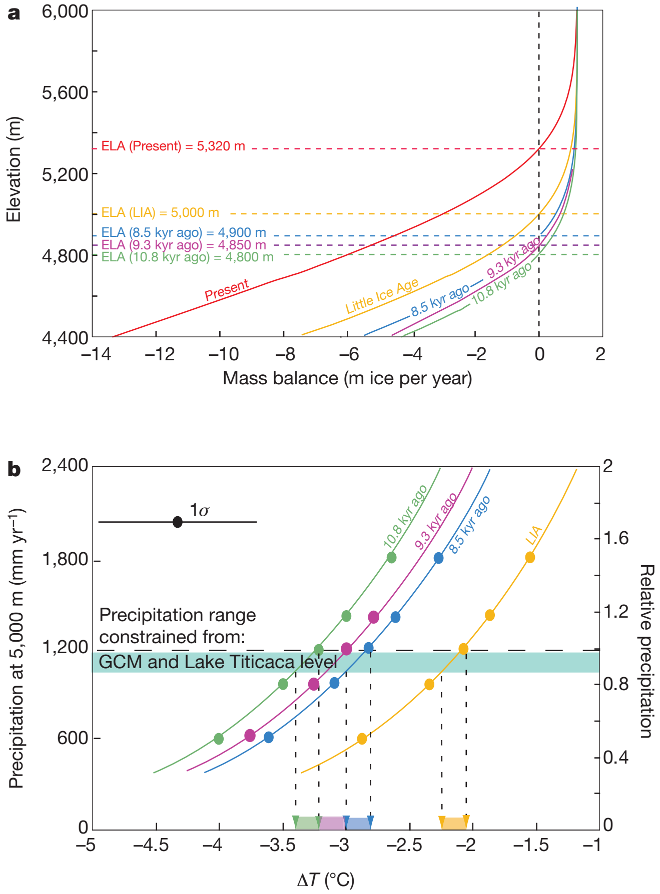

Figure 2 | Palaeoclimatic reconstructions of the Telata glacier. **a**, Plot of mass balance against elevation for the present day (red curve), 10.8 kyr ago (green), 9.3 kyr ago (purple), 8.5 kyr ago (blue) and Little Ice Age (yellow). Dashed lines, altitudes of the ELA from 10.8 kyr ago to present. The present-day mass balance curve at the Zongo glacier is characterized by an ELA at 5,320 m a.s.l. **b**, Palaeoclimatic conditions at 5,000 m a.s.l. required to reproduce the glacier extent during the past 10.8 kyr. Changes in temperature (ΔT) are plotted against changes in precipitation. Left-hand y axis, absolute precipitation at 5,000 m a.s.l.; right-hand y axis, relative precipitation at 5,000 m a.s.l., normalized to present day value. The 1σ error bar shows the temperature uncertainty arising from the model assumptions. Sensitivity tests indicate that the temperature uncertainty is ±0.7 °C. Dashed vertical lines with coloured arrows indicate the range of possible temperature depression for 10.8 kyr ago (green), 9.3 kyr ago (purple), 8.5 kyr ago (blue) and the Little Ice Age (yellow) under a scenario of 0–12% precipitation reduction.

The model does not, however, provide a unique solution for the inferred palaeoclimatic conditions, as there is a range of temperature/precipitation combinations that can maintain one given glacier extent. We thus used independent estimates of precipitation from six mid-Holocene PMIP-II general circulation model (GCM) simulations (Supplementary Information section 2, Supplementary Fig. 6). The GCM simulations show a 4–12% decrease in annual precipitation in the Cordillera Real compared to the pre-industrial period during the mid-Holocene. Additional simulations with one of the PMIP-II GCMs (IPSL-CM4[18]) for the early Holocene (9.5 kyr before present) reveals a 12% decrease, while no significant differences are simulated when comparing late Holocene (4 kyr before present) to pre-industrial conditions (not shown). Even though the amplitude varies, the consistency among PMIP-II models suggests that a slight precipitation decrease is a robust result for the mid-Holocene and might be independent of the GCM used (Supplementary Fig. 6). Moreover, previous studies depicted rather dry mid-Holocene conditions in the region compared to the late Holocene[11,19,20], in agreement with the results from the GCMs. Importantly, the relatively low levels of Lake Titicaca during the Holocene[10,20] indicate that the regional precipitation did not exceed its present level (Fig. 2)[21].

In order to assess the uncertainty arising from these palaeoprecipitation estimates, we used a range of precipitation changes varying from 88% to 100% of modern conditions for the whole Holocene period to constrain our glaciological model (Fig. 2). This approach indicates that within the range of uncertainties in precipitation changes, the glacier extents at 10.8 kyr ago, 8.5 kyr ago and during the LIA required a temperature change of $-3.3 \pm 0.8\,^{\circ}$C, $-2.9 \pm 0.8\,^{\circ}$C and $-2.1 \pm 0.8\,^{\circ}$C, respectively (Fig. 2b).

We observe that the tropical Telata glacier underwent a decline over the past 11 kyr that mirrors low-frequency insolation changes, suggesting a possible external forcing amplified by regional mechanisms (see below). The Telata glacier is indeed located in a region where precipitation is fed predominantly by summer monsoonal easterly airflow originating over the tropical Atlantic Ocean[22] (Fig. 3) (Supplementary Information section 2). The South American summer monsoon (SASM) is likely to have been the dominant moisture source for the glacier over the past 11 kyr (ref. 22), and glacier mass balance thus could have responded sensitively to precession-driven changes in SASM-related moisture supply. Documented regional climate changes attest that the early Holocene summer insolation minimum made the SASM weaker[18] than it was in the late Holocene period, favouring a northerly mean latitude for the intertropical convergence zone[23,24] (ITCZ; Fig. 4b, c) while cooling the eastern equatorial Pacific Ocean[24] (Fig. 4c). The rapid retreat of Telata between 11 and 8.5 kyr ago could have occurred in response to this quite rapid and significant decrease in SASM intensity. In addition to the summer insolation minimum, Northern Hemisphere land ice melting and the subsequent freshwater inflow in the North Atlantic from the late glacial to the early Holocene might have also favoured a southward shift of the ITCZ and the weakening of the SASM[23–25]. Coupled GCM simulations (Supplementary Information section 2) are able to reproduce the observed colder eastern equatorial Pacific Ocean and weaker SASM as a direct response to insolation changes only (Fig. 3).

On the other hand, our PDD model reveals that rather cold conditions over the Telata glacier in the late glacial, early Holocene and LIA were sufficient to maintain the observed past glacier extents. The recovering and strengthening of the SASM over the course of the Holocene period after 8.5 kyr before present must have led to a precipitation increase over the glacier. However, the moraine chronology shows that the glacier was still retreating during this period, despite increased moisture availability. This result suggests that the substantial increase in temperature and solar radiation from 8.5 kyr before present to the

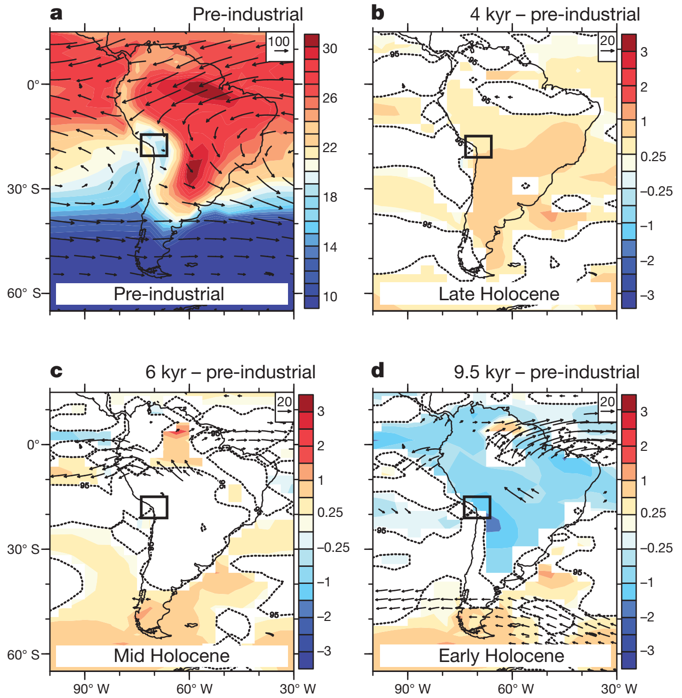

Figure 3 | Changes in surface temperature and atmospheric moisture transport simulated for December by the IPSL-CM4 GCM. The colour shading shows temperature in °C (**a**) or temperature difference (**b**–**d**). The dashed line indicates significant differences between Holocene and pre-industrial simulations at $P = 0.05$; vectors indicate the vertically integrated atmospheric latent heat transport in W m^{-2}. The reference vector is boxed at top right of each panel. **a**, Pre-industrial conditions; **b**, difference between 4 kyr BP and pre-industrial; **c**, difference between 6 kyr BP and pre-industrial; **d**, difference between 9.5 kyr BP and pre-industrial. Telata region shown boxed.

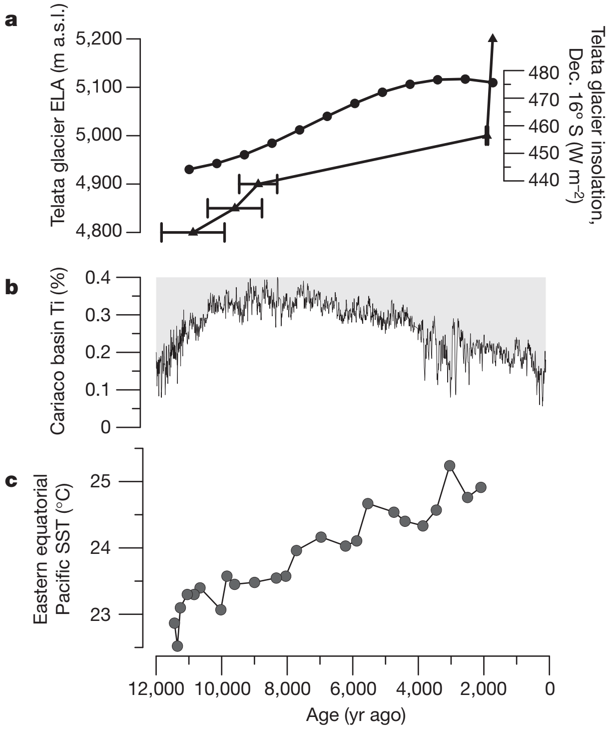

Figure 4 | Changes of the Telata glacier compared to tropical climate proxies. **a**, Triangles, changes in the ELA of the Telata glacier (frontal moraine dated by ^{10}Be); circles, December insolation changes at 16° S. Error bars (±s.e.m.) on each ^{10}Be group indicate uncertainty associated with the mean age and account for analytical uncertainty only. (Note that to these analytical uncertainties has to be added 9% uncertainty linked to the production rate when comparing theses ages with other chronological reconstructions.) **b**, Titanium concentration in Cariaco basin sediment[23]. **c**, SST in the eastern tropical Pacific[24].

late Holocene outweighed the impact of increased precipitation on the Telata glacier mass balance[26]. Energy balance measurements reveal that modern austral summer short-wave radiation controls glacier ablation and glacier mass balance through albedo feedbacks[15–17]. An increase in summer insolation would enhance regional temperature and affect the albedo (for example, through a shift in the rain–snow line) and hence increase glacier melt, in agreement with our PDD results. Although the lack of alternative proxy records precludes an independent confirmation of the temperature increase in the Telata region, the glacier retreat from the early Holocene to the LIA is consistent with progressively warmer eastern Pacific sea surface temperatures[24] (SSTs), a phenomenon also observed today[27] (Fig. 4a–c). The coupled GCM simulates an increase in surface temperature over both the eastern equatorial Pacific (+2 to +2.5 °C) and tropical South America (+1.5 to +2 °C) as a first order response to insolation forcing from the early Holocene to pre-industrial conditions (Figs 3, 4). A progressive warming throughout the Holocene is thus in agreement with the GCM results (Fig. 4).

Our results indicate that increasing insolation and a warming of 3.3 °C (±0.8 °C) was probably sufficient to counterbalance the strengthening of the SASM through the Holocene, thereby leading to the Telata glacier retreat. Future projections estimate a 4–5 °C warming in the high mountains of the tropical Andes[28,29] by 2100; this warming is larger than our estimate for the entire Holocene, which led to a rise in ELA of 520 m and a decrease of 92% in the surface area (a 2.4 km retreat) of the Telata glacier.

METHODS SUMMARY

Palaeoglacial extents were documented from moraine records. Ice volumes, mass balance variations with elevation, ELA and the associated climatic conditions corresponding to palaeomoraines were estimated with the PDD model combined with a dynamic ice flow model[14]. Current observations on the Zongo glacier reveal that variables affecting albedo directly, such as precipitation, or indirectly, such as temperature (through the elevation shift of the rain–snow line), have a strong effect on ablation and hence on the specific mass balance. In addition, current observations also demonstrate that austral summer precipitation is another important factor controlling accumulation over Bolivian glaciers at interannual timescales and therefore variability of the glacier's mass balance[27]. However, monthly and annual air temperature are significantly correlated with glacier mass balance because they are well correlated with the main energy fluxes through the ablation and accumulation processes over tropical glaciers at such timescales[17]. Hence, we used the PDD model that assumes both precipitation and temperature as fundamental variables of the mass balance. This model also integrates the effect of solar radiation and uses different melting factors for ice and snow[14]. For the period 1991–2008, the annual mean temperature measured on the lateral moraine of the Zongo glacier at 5,000 m a.s.l. was ~0.5 °C, and mean annual precipitation was 1,200 mm yr^{-1}.

Received 3 March; accepted 21 April 2011.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements Financial support was provided by the French INSU programme 'LEVE', the French ANR Escarcel programme no. 06-Vuln-010, UR Great Ice at IRD, and the French ANR El Paso programme no. 10-Blan-608-01. We thank P. Ginot, E. Perroy, E. Ramirez and the Bolivian authorities for facilitating our field work in the Zongo valley. The ^{10}Be measurements were performed at the ASTER AMS national facility (CEREGE, Aix en Provence), which is supported by INSU/CNRS, the French Ministry of Research and Higher Education, IRD and CEA. We are grateful to L. Léanni for handling the necessary physical and chemical preparations before the ^{10}Be measurements, and to M. Arnold, G. Aumaître and K. Keddadouche for help during the ^{10}Be AMS measurements. We acknowledge the international modelling groups for providing their data for analysis. The PMIP2/MOTIF Data Archive is supported by CEA and CNRS, and was funded by the EU project MOTIF (EVK2-CT-2002-00153) and the Programme National d'Etude de la Dynamique du Climate (PNEDC). The analyses were performed using model versions available on 23 May 2009 (http://pmip2.lsce.ipsl.fr/). Computing time to run the IPSL model was provided by CEA. We are grateful for the assistance received from IHH (Instituto de Hidraulica e Hídrologia) and UMSA (Universidad Mayor de San Andrés, La Paz).

Author Contributions V.J. and D.B. conducted the field work on Telata; M.K. and P.B. performed the GCM modelling; P.-H.B. developed the PDD numerical modelling. J.-E.S., P.W. and V.F. provided ablation and climatic data from the Zongo glacier and helped in developing the glacier mass balance model and with the energy balance interpretation. D.L.B. and R.B. participated in analysing and interpreting the cosmogenic data. V.J., M.K., V.F., D.B., D.G., M.-P.L., P.W., P.-H.B., J.-E.S., R.B., D.L.B. and M.V. interpreted the data and wrote the paper.

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