

Review article of the
current state of
glaciers in the
tropical Andes

A. Rabatel et al.

Review article of the current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change

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Abstract

The aim of this paper is to provide the community with a comprehensive overview of the studies of glaciers in the tropical Andes conducted in recent decades leading to the current status of the glaciers in the context of climate change. In terms of changes in surface area and length, we show that the glacier retreat in the tropical Andes over the last three decades is unprecedented since the maximum extension of the LIA (mid 17th–early 18th century). In terms of changes in mass balance, although there have been some sporadic gains on several glaciers, we show that the trend has been quite negative over the past 50 yr, with a mean mass balance deficit for glaciers in the tropical Andes that is slightly more negative than the computed global average. A break point in the trend appeared in the late 1970s with mean annual mass balance per year decreasing from -0.2 m w.e. in the period 1964–1975 to -0.76 m w.e. in the period 1976–2010. In addition, even if glaciers are currently retreating everywhere in the tropical Andes, it should be noted that as a percentage, this is much more pronounced on small glaciers at low altitudes that do not have a permanent accumulation zone, and which could disappear in the coming years/decades. Monthly mass balance measurements performed in Bolivia, Ecuador and Colombia showed that variability of the surface temperature of the Pacific Ocean is the main factor governing variability of the mass balance variability at the interannual to decadal time scale. Precipitation did not display a significant trend in the tropical Andes in the 20th century, and consequently cannot explain the glacier recession. On the other hand, temperature increased at a significant rate of 0.10 °C decade⁻¹ in the last 70 yr. The higher frequency of El Niño events and changes in its spatial and temporal occurrence since the late 1970s together with a warming troposphere over the tropical Andes may thus explain much of the recent dramatic shrinkage of glaciers in this part of the world.

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1 Introduction

The tropical Andes is host to more than 99% of all tropical glaciers (Kaser, 1999) between Peru (71%), Bolivia (20%), Ecuador (4%) and Colombia-Venezuela (4%). Glacier inventories have been conducted in almost all tropical mountain ranges (Jordan, 1991; Poveda and Pineda, 2009; UGRH, 2010) from 1975 in Bolivia to 2006 in Peru. Based on these inventories and current rates of retreat documented for a sample of glaciers in different cordilleras, Francou and Vincent (2007) estimated the total glacier surface-area in the intertropical Andes in the early 2000s to be around 1920 km².

The Intergovernmental Panel on Climate Change (IPCC) pointed to the role of mountain glaciers as key indicators of recent climate change (Lemke et al., 2007). Tropical glaciers are known to be especially sensitive to climate change (e.g. Hastenrath, 1994; Kaser and Osmaston, 2002). Due to the specific climate conditions in the tropical zone, ablation occurs all year round on the lowest part of the glaciers resulting in a short-time response of the position of the glacier terminus to changes in mass balance, and consequently to changes in climate (e.g. Francou et al., 1995, 2003, 2004; Wagnon et al., 1999). Recently, using englacial temperature measurements in a 138 m deep borehole drilled near the summit of Illimani (6340 m a.s.l., Bolivia), Gilbert et al. (2010) evidenced a warming trend at high elevations during the 20th century. This result is in good agreement with air-temperature measurements and reanalysis data presented by Vuille et al. (2003) and Bradley et al. (2009), showing an increase of 0.10 °C decade⁻¹ across the tropical Andes for the period 1939–1998. An increase of more than +4 °C at elevations above 4000 m a.s.l. is projected for the 21st century using IPCC scenario A2 (Bradley et al., 2006; Urrutia and Vuille, 2009). With no change in precipitation, such a temperature change could lead to a major reduction in glacial coverage and even to the complete disappearance of small glaciers, whose upper reaches are located close to the current equilibrium-line altitude (ELA). This is a serious concern because a large proportion of the population lives in arid regions to the West of the Andes (especially in

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Peru and Bolivia, where the percentage of glaciers is the highest). As a consequence, the supply of water from high altitude glacierized mountain chains is crucial for agricultural and domestic consumption as well as for hydropower (Vergara et al., 2007). This is all the more true since these regions also exhibit a combination of warm and dry conditions as a part of the seasonal cycle, with limited seasonal temperature variability and a dry season lasting from May/June to August/September (Kaser et al., 2010). As a consequence, mountain glaciers in the tropical Andes act as critical buffers against highly seasonal precipitation at times when rainfall is low or even absent (Vuille et al., 2008a).

To better understand glaciological processes, to link climate parameters and their variability to glacier mass balance, and to document current glacier changes, permanent glacier monitoring networks have been set up in each country between Colombia and Bolivia. The oldest data series are available in Peru where partial surveillance of glaciers began in the early 1970s. Since the early 1990s, an important effort has been made by IRD (the French Institute of Research and Development), in association with Andean partners in Bolivia, Ecuador and Peru, as well as other international scientific teams such as: the “Tropical Glaciology Group” at the University of Innsbruck (Austria), the Department of Geography at the Ohio State University (USA) or the Department of Geography at the University of Zurich (Switzerland). The observation system mainly consists of measuring the glacier mass balance using glaciological and hydrological methods, and of measuring the glacier surface energy balance. In parallel, remote-sensing studies have been performed using aerial photographs and satellite images to reconstruct changes in the volume, surface area and length of a large number of glaciers in the area since the middle of the 20th century.

In addition to this permanent monitoring, considerable effort has been made to reconstruct glacier fluctuations from moraine evidence since the Little Ice Age (LIA) maximum across the tropical Andes (e.g. Rabatel et al., 2005a, 2008a; Jomelli et al., 2009). Finally, ice cores have been retrieved from several summits in Ecuador, Peru and Bolivia which revealed important information about climate variations at a multidecadal

time-scale over the last millenium and about climate warming during the 20th century (e.g. Thompson et al., 1985, 2006; Hoffman et al., 2003; Ramirez et al., 2003; Ginot et al., 2010; Gilbert et al., 2010).

The objective of this review is to provide the scientific community with a comprehensive overview of studies performed on glaciers in the tropical Andes in recent decades, which allow the current status of the glaciers to be determined. Research questions addressed also include whether the glacial retreat of tropical glaciers in recent decades is unprecedented since the LIA, and whether the glacial recession in the tropical Andes is related to the observed increase in atmospheric temperature. These are important issues to estimate the future behavior of glaciers and their impacts on the hydrological functioning of high-altitude glacierized watersheds in coming decades.

2 General settings and methodologies

2.1 Climate settings

From a climatological point of view, the intertropical zone can be divided into two zones with different characteristics. Troll (1941) distinguished the inner tropical climate with more or less continuous precipitation throughout the year and the outer tropical climate which when subtropical conditions prevail, is characterized by a dry season in May to September and when tropical conditions prevail by a wet season in October to March. The tropical climate is characterized by homogeneous temperature conditions throughout the year with a slight seasonality of air temperature in the outer tropics (1 °C to 2 °C higher temperatures during the austral wet summer in October to March, than during the austral dry winter in May to September). At low latitudes, incident solar radiation is also more or less constant throughout the year, as the seasonality of the extra-terrestrial irradiance in the outer tropics is attenuated by pronounced cloud seasonality (maximum cloud cover during austral summer). In the humid inner tropics, stable humidity conditions cause accumulation and ablation to occur simultaneously

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throughout the year, whereas the outer tropics are characterized by pronounced seasonality of specific humidity, cloud cover and precipitation. Thus, notable accumulation occurs only during the wet season and ablation, which is strong during the wet months, is reduced for the rest of the year (Kaser, 2001). Precipitation mainly results from an easterly flow of moisture from the Amazon basin (e.g. Garreaud et al., 2003). At inter-annual timescales, the strong variability of summer precipitation has been described in many studies and there is general agreement that a significant fraction of this variability is related to the El Niño–Southern Oscillation (ENSO) phenomenon (e.g. Francou and Pizarro, 1985; Aceituno, 1988; Vuille et al., 2000; Garreaud and Aceituno, 2001). These studies concluded that El Niño years (warm phase of ENSO) tend to be warm and dry, while La Niña years (ENSO cold phase) are associated with cold wet conditions on the Altiplano. However, the climate characteristics of La Niña/El Niño are not uniform across the intertropical Andes region. Even at the scale of a country, the consequences of an El Niño event may vary considerably, for instance between the northern coast of Peru and the Southern Peruvian Altiplano region.

2.2 Reconstruction of LIA glacier changes

In the early 1980s, Hastenrath (1981) and Clapperton (1983) already mentioned that glaciers in the tropical Andes were much larger during the LIA than today, but the date of their maximum extent and the stages of their subsequent retreat remained highly conjectural. Historical sources and mining settlements established in the colonial period (Broggi, 1945) 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). Some authors tried to date the LIA in the tropical Andes using glacier evidence with ^{14}C dating (Gouze et al., 1986; Seltzer, 1992). In Bolivia, Gouze et al. (1986) suggested 670–280 calyr BP as the interval displaying maximum ice extension. In Peru, on the basis of evidence found in the ice core retrieved on the Quelccaya ice cap, Thompson et al. (1986) assumed that the LIA lasted from AD 1500 to AD 1900. Lichenometry has also been used to date very well preserved moraines

on glacier forelands (see the maps of the Bolivian eastern cordillera by Jordan, 1991, where the main moraine stages are represented). Müller (1985) applied this technique for relative dating in Bolivia, and Rodbell (1992) dated Peruvian LIA moraines to the period 750–1900 AD, but without providing a detailed chronology of glacier fluctuations during the period.

New insight into glacier fluctuations during the LIA concerning the entire intertropical Andes has been gained in the past decade thanks to moraine dating using lichenometry. Systematic measurements of *Rhizocarpon Geographicum* sp. were made on each moraine in several proglacial margins in Bolivia (Rabatel et al., 2005a, 2008a), Peru (Solomina et al., 2007; Jomelli et al., 2008), and Ecuador (Jomelli et al., 2009). A new statistical approach was developed to process data based on the extreme values theory, as the largest lichens measured for moraine dating are extreme values (Cooley et al., 2006; Naveau et al., 2007).

Glacier length, surface area and ELA for the LIA maximum and the following moraine stages were reconstructed using digital elevation models (DEM) on the basis of the moraines (Rabatel et al., 2006, 2008a; Jomelli et al., 2009). For five glaciers in Cerro Charquini Massif in Bolivia, Rabatel et al. (2006) computed changes in volume between the most important moraine stages by reconstructing glacier hypsometry.

2.3 20th century observations: from field measurements to remote-sensing studies

2.3.1 Pioneering studies

Unlike mid-latitude glaciers where continuous mass balance series have been available for five to six decades, information on glacier in the tropical Andes was very scarce before 1990. Data on glacier terminus fluctuations have been available for four glaciers in the Peruvian Cordillera Blanca since the late 1940s, and since the late 1970s, a few years of mass balance measurements for three of them (Kaser et al., 1990; Ames and Francou, 1995; Hastenrath and Ames, 1995a,b; Ames and Hastenrath, 1996).

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2.3.2 Monitoring mass balance in the field

In 1991, a project by the French IRD and Bolivian partners enabled instrumentation of two glaciers for a full permanent monitoring of their mass balance, hydrological balance, and surface energy balance (Francou and Ribstein, 1995; Francou et al., 1995). The same monitoring system was set up in Ecuador in 1995 (Francou et al., 2000), in Peru in 2003, and in Colombia starting in 2006 (Table 1 and Fig. 1). This collaborative effort is now part of a permanent monitoring network called GLACIO-CLIM (<http://www.lgge.ujf-grenoble.fr/ServiceObs/index.htm>), and a joint international project called GREAT ICE, involving academic and research institutions in France, Bolivia, Ecuador and Peru. In addition, two of the glaciers that belong to this monitoring network, Zongo in Bolivia and Antisana 15 in Ecuador, are among the benchmark glaciers in the tropics referenced by the World Glacier Monitoring Service (WGMS, 2011).

Glacier mass balance was computed using the glaciological method (Paterson, 1994). In the lower part of the glacier, monthly measurements (in Bolivia, Ecuador and Colombia) of stake emergence were made using a network of 10 to 25 stakes (depending of the glacier). Snow height and density measurements are required as well as stake emergence measurements because snowfall can occur at the glacier surface at any time during the year. In the upper part of the glacier, net accumulation (snow height and density) was measured at the end of the hydrological year at two to four locations. To compute the annual mass balance of the glaciers, glacier hypsography was calculated using DEM has been defined p. 8, l. 15 computed by aerial photogrammetry (Bolivia and Ecuador) or using maps from the National Geographical Institute (Peru, Colombia).

2.3.3 Surface energy balance: measurements and modeling

Climate controls glacier mass balance through energy and mass fluxes at the ice or snow surface. The energy available for melt can be calculated as the residual of the

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energy balance equation whose main terms on temperate tropical glaciers are short-wave and long-wave radiation fluxes and the turbulent fluxes of sensible and latent heat. Radiation fluxes on glaciers can be accurately measured with radiometers whereas turbulent fluxes are generally derived from aerodynamic profile methods with one or two levels of wind, temperature and humidity measurements. These methods are not very accurate and require parameters such as roughness lengths or eddy diffusivity coefficients. Measurements of energy fluxes on tropical glaciers began in the 1960s but are still relatively rare (e.g. Platt, 1966; Hastenrath, 1978; Hardy et al., 1998). In 1995, automated weather stations began to be used to monitor surface energy fluxes in the ablation area of Zongo Glacier, in Bolivia, and Antizana 15 Glacier, in Ecuador (Wagon et al., 1999; Favier et al., 2004b).

The interpretation of point-scale energy flux measurements can lead to erroneous generalizations of melt characteristics when they are extrapolated to the whole glacier. For example, albedo is highly variable near the snowline, so that the contribution of solar radiation to melt energy depends on the location of the weather station. A distributed energy balance model is thus required to investigate the link between atmospheric forcing and the total glacier mass balance and to quantify the contribution of glacier melt to water resources downstream. With the objective of investigating seasonal climate forcing on the mass balance and meltwater discharge of tropical glaciers, Sicart et al. (2011) applied the spatially distributed energy balance model of Hock and Holmgren (2005) to the Bolivian Zongo Glacier at an hourly time step for an entire hydrological year. The model calculates the surface energy fluxes for each glacier grid cell from measurements collected at a weather station located in the ablation area. It is based on equations of mass and energy conservation and the parameters theoretically have a physical interpretation (Beven, 1989), so they can be linked to measurable physical quantities. The model had to be adjusted to tropical high mountains mainly for the calculation of albedo, due to the frequent alternation of melt and snowfall periods during the wet season, and of long-wave incoming radiation, due to the pronounced seasonality of sky emission.

2.3.4 Contribution of remote sensing

To complete glaciological data time series in terms of changes in surface area and volume before the beginning of field measurements, and to calculate these changes at a regional scale, remote-sensing techniques have proved to be very efficient. Brecher and Thompson (1993) used terrestrial photogrammetry to quantify the retreat of Qori Kalis Glacier (Quelccaya ice cap, Peru). Aerial photographs (available since the 1950s) and satellite images (available since the late 1970s) have been widely used for glacier inventories (Jordan, 1991; Georges, 2004; Silverio and Jaquet, 2005; Jordan et al., 2005; Morris et al., 2006; Raup et al., 2007; Racoviteanu et al., 2007; Poveda and Pineda, 2009; UGRH, 2010) and to quantify variations in glacier surface area at a decadal to interannual timescale since the mid-20th century (Rabatel et al., 2006; Basantes, 2010; Caceres, 2010; Collet, 2010).

Variations in glacier volume at a decadal time scale since the mid-1950s were reconstructed for 26 glaciers in Bolivia (Rabatel et al., 2006; Soruco et al., 2009a,b) and two glaciers in Ecuador (Caceres, 2010) on the basis of aerial photograph pairs processed using photogrammetric restitution techniques. For three glaciers in the Cordillera Blanca, Peru, Mark and Seltzer (2005) assessed changes in volume between 1962 and 1999 using similar photogrammetric techniques, while Salzmann et al. (2012) applied a combined remote sensing data and modeling approach to estimate changes in volume in the Cordillera Vilcanota, Southern Peru for a similar period. This type of geodetic method to compute volume variation over the whole glacier surface is very useful to validate and adjust mass balance data calculated using both glaciological and hydrological methods. Such an adjustment was performed for Zongo Glacier in Bolivia by Soruco et al. (2009b).

Finally, Rabatel et al. (2012) showed that the method to reconstruct annual mass balance based on snowline altitude (SLA) measured on satellite images and used as a proxy of the ELA can be used for glaciers in the outer tropical zone. This method was first developed for mid-latitude glaciers (Rabatel et al., 2005b, 2008b), and was then

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successfully tested, validated, and applied on 11 Bolivian glaciers (Bermejo, 2010; Consoli, 2011).

2.3.5 Climate data

With the aim of linking changes in glacier mass balance with climate variability and atmospheric circulation at a regional to global scale, many recent studies have focused on variables that are relevant for the glacier energy balance, such as temperature, precipitation, humidity and convective cloud cover (Wagnon et al., 1999; Francou et al., 2003, 2004; Favier et al., 2004a; Sicart et al., 2005; Vuille et al., 2008b; Salzmann et al., 2012). A common theme in all these studies is the significant role played by the tropical Pacific Sea surface temperature (SST) and the ENSO phenomenon in modulating glacier mass balance at interannual time scales. A summary review of these studies was presented by Vuille et al. (2008a). Here, we build on this earlier work by relying on temperature data from NCEP/NCAR reanalysis (Kalnay et al., 1996). Recent studies showed that this data set simulates near-surface temperature trends in the Andes with reasonable accuracy (e.g. Bradley et al., 2009). Nonetheless it should be kept in mind that here we are considering free-tropospheric temperature based on a 2.5° resolution. Hence actual temperature measurements on or near the glaciers, for example on Zongo or Antisana glaciers, may show absolute temperature readings that are somewhat higher than reanalyzed data. However, reanalyzed temperature data and surface temperatures are significantly correlated, as changes in temperature are similar at the surface and in the adjacent free air (Bradley et al., 2006).

3 Results

3.1 Glacier changes since the LIA maximum

Recent studies focused on glacier variations in the intertropical Andes from Venezuela to Bolivia during the LIA (e.g. Rabatel et al., 2005a, 2006, 2008a; Polissar et al., 2006;

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Solomina et al., 2007; Jomelli et al., 2008, 2009). Figure 2 (upper panel) summarizes information on glacier advances in the intertropical Andes documented from moraine stages and lake sediments. An early glacial advance at the beginning of the last millennium was documented in Venezuela from lake sediments (Polissar et al., 2006) and for some glaciers in Peru and Bolivia from moraine stages (Jomelli et al., 2009). However, this 14th century glacial stage is absent in most valley glaciers, suggesting that younger glacial advances extended further than those that occurred in the 14th century.

The LIA maximum extension period in the outer tropics is dated to the 17th century with dates varying slightly from one mountain range to another. The lichenometric dates are around 1630 ± 27 AD in Peru (Solomina et al., 2007; Jomelli et al., 2008), and between 1657 ± 24 AD and 1686 ± 26 AD in Bolivia (Rabatel et al., 2005a, 2008a). These dates are concomitant with another glacial advance documented from lake sediments in Venezuela (Polissar et al., 2006). In the inner tropics, the LIA maximum extension occurred in two distinct periods (Jomelli et al., 2009). For glaciers with a maximum altitude above 5700 m a.s.l., it was dated to the early 18th century (1730 ± 14 AD). For those whose maximum altitude is lower, the maximum extension period was dated to the early 19th century (1830 ± 11 AD). This moraine stage can also be found along proglacial margins of glaciers located on summits above 5700 m a.s.l., but testifies to a smaller glacial advance than the one that occurred during the maximum extent. The advance was also documented from reliable historical sources in Ecuador (Francou, 2004). Finally, this early 19th century advance was also concomitant with an advance phase documented from lake sediments in Venezuela (Polissar et al., 2006).

Following the period of maximum extension, the evolution of glaciers in the inner and outer tropics was remarkably homogeneous (Jomelli et al., 2009). A slow withdrawal occurred during the late 18th and first half of the 19th century. In the outer tropics, among the moraine stages observed along the proglacial margins, two are clearly the consequence of an advancing glacier because they partly removed previous deposits (Rabatel et al., 2008a); they are dated to about 1730 AD (LIA maximum for Ecuadorian glaciers on summit higher than 5700 m a.s.l.) and about 1800 AD. After 1840 AD,

withdrawal was more pronounced and accelerated in the late 19th century (from about 1870 to the early 20th century) in both inner and outer tropics (Jomelli et al., 2009).

The withdrawal from the post-LIA maximum extension and the absence of a major readvance in the 19th century (equivalent to the magnitude of LIA maximum) in the entire tropical belt are the main differences from the evolution of glaciers in temperate latitudes of the Northern Hemisphere. In Bolivia, Rabatel et al. (2006) observed that glaciers retreated by about 1000 m in length from the mid-17th to the late 19th century.

Figure 3 shows changes in surface area of Bolivian glaciers since the LIA maximum. Only the best documented glaciers for both the LIA period (Rabatel et al., 2008a) and the recent decades are plotted. This figure shows the current glacier withdrawal compared to the retreat that occurred four centuries ago. Two main features are:

- A general withdrawal with two periods of accelerated retreat: one in the late 19th century and one in the last three decades, the latter being the most pronounced. The changes in surface area that occurred during the 18th and 19th centuries are homogenous even though the glaciers differ in size (ranging from 0.5 to 3.3 km²), aspect (all are represented) and maximum altitude (ranging from 5300 m to 6000 m a.s.l.).
- Since the middle of the 20th century, the rate Zongo Glacier retreated has differed from that of other glaciers. Within the sample of glaciers plotted in Fig. 3, Zongo Glacier is the only one with an accumulation area above 5500 m a.s.l. (reaching 6000 m a.s.l.) and hence still has a large accumulation zone. Small glaciers at lower altitudes (i.e. <5400 m a.s.l.), that have no accumulation zone have almost completely disappeared.

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3.2 Changes in glacier surface area in recent decades

3.2.1 The Peruvian Andes

The Peruvian Andes are probably the best documented glacial area. In the Cordillera Blanca, Kinzl (1969) reported that glacier retreat accelerated during the late 19th century before slowing 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). In the period from 1950 to 1970, glaciers retreated very slowly (Hastenrath and Ames, 1995a). This retreat was followed by a general acceleration (Ames and Francou, 1995; Kaser and Georges, 1997). Mark and Seltzer (2005) showed that glacier surface area decreased by about 35 % in the Queshque Massif (southern part of the Cordillera Blanca) between 1962 and 1999. Raup et al. (2007) documented a 20 % to 30 % retreat between 1962 and 2003 (depending on the source considered for 1962) for glaciers in the Huandoy-Artesonraju Massif (northern part of the Cordillera Blanca). At the scale of the whole Cordillera Blanca, several inventories were performed using digitized maps and satellite images (e.g. Georges, 2004; Silverio and Jaquet, 2005; Racoviteanu et al., 2008; UGRH, 2010). Results differed slightly because of the methods used to delineate glacier contours, for example whether or not perennial snow fields were included. But the main conclusion was the same, i.e. a marked glacier retreat in the last two decades. UGRH (2010) reported a 27 % loss between the 1960s and the 2000s, from 723 km² to 527 km². Intermediate estimations show that the mean annual loss in surface area has increased since the late 1990s (Fig. 4). For the second largest glacierized mountain range in Peru, the Cordillera Vilcanota in Southern Peru, Salzmann et al. (2012) reported a 32 % loss in area between 1962 and 2006, including an almost unvarying glacier area between 1962 and 1985. For Qori Kalis, an outlet glacier of Quelccaya ice cap in the Cordillera Vilcanota, Brecher and Thompson (1993) and Thompson et al. (2006) noted a 10 times greater loss in area between 1991 and 2005 than between 1963 and 1978, with an accelerated retreat in the 1990s. Finally,

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Racoviteanu et al. (2007) reported that the glaciated area on Coropuna (Cordillera Ampato, Southern Peru) shrank by about 26 %, from 82.6 km² in 1962 to 60.8 km² in 2000.

Figure 5 shows changes in the length of five glaciers in the Peruvian Cordillera Blanca. Direct annual measurements began between 1968 and 1980, but additional information for 1949 was added based on aerial photographs. For glaciers for which data are available for the 1970s, a break point in the trend appeared in 1976–77. Before this date, changes in glacier length were very limited; Broggi Glacier even advanced in the early 1970s. Since the end of the 1970s, glacial withdrawal has been significant and the glaciers have retreated between 500 and 600 m in length. El Niño years (e.g. 1982–83, 1997–98, 2004–05) resulted in a more pronounced retreat; whereas persistent La Niña conditions at the turn of the 21st century resulted in a slight slowdown in the retreating trend.

3.2.2 The Bolivian Andes

In Bolivia, Jordan (1991) published a complete inventory of glaciers in both Cordilleras (oriental and occidental), on the basis of aerial photographs taken in 1975 and field campaigns from 1984. Total glacierized area was estimated to be about 560 km². Although there has been no more recent glacier inventory of these cordilleras, glacier changes in the Cordillera Real (part of the Cordillera oriental) have been documented (Ramirez et al., 2001; Rabatel et al., 2006; Soruco et al., 2009a,b). Figure 5 illustrates changes in surface area of the three best documented glaciers of the Cordillera Real: Chacaltaya Glacier (Francou et al., 2000; Ramirez et al., 2001), Charquini Sur Glacier (Rabatel et al., 2006) and Zongo Glacier (Soruco et al., 2009b). Before the beginning of direct measurements in the early 1990s, estimates of surface areas were retrieved from aerial photographs after 1940 at a decadal time scale. Zongo and Charquini Sur glaciers showed a similar pattern as the one previously described for the Peruvian glaciers, i.e. an almost balanced situation during the 1950s and 1960s, which, at the end of the 1970s, changed to a retreat that varied according to the size and maximum

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altitude of the glacier concerned. Chacaltaya Glacier retreated throughout the period, but the retreat started to accelerate in the late 1970s.

3.2.3 The Ecuadoran Andes

In Ecuador, results obtained by Jordan et al. (2005) using photogrammetry on the Cotopaxi Volcano (5897 m a.s.l.) showed that Cotopaxi glaciers remained almost stagnant between 1956 and 1976 and then lost approximately 30 % of their surface area between 1976 and 1997. The calculated lost of total mass (thickness) of selected outlet glaciers on Cotopaxi between 1976 and 1997 was 78 m, or 3–4 m.w.e.yr⁻¹. Figure 6 shows recent updates mostly based on satellite images (LANDSAT, ASTER and ALOS) which enabled reconstruction of changes in glacier surface area on Cotopaxi Volcano, and additionally, documented glacier shrinkage on both Antisana (5753 m a.s.l.) and Chimborazo (6268 m a.s.l., not shown in Fig. 6) since the mid-20th century (Basantes, 2010; Caceres, 2010; Collet, 2010). These studies showed that over the 1962–1997 period, the surface area of the glaciers on Chimborazo decreased from 27.7 to 11.8 km² (Caceres, 2010), which represents a loss of 57 % or 1.6 % yr⁻¹ on average (Fig. 4). For Cotopaxi and Antisana volcanoes, the loss in surface area was 37 % and 33 %, respectively for the period 1979–2007. Intermediate information indicates that the retreat increased during the second part of the period (Fig. 4). Changes in surface area computed from satellite images at an almost annual resolution on glaciers Antisana 12 and 15 also document the increased loss of surface area since the early 1990s (Fig. 5). However, small advances by both glaciers occurred in 2000 and 2008. These advances match positive mass balance years and indicate the rapid response of Ecuadorian glaciers to changes in mass balance.

3.2.4 The Andes of Colombia and Venezuela

In Colombia, a compilation of glacier surface-area mapping at the scale of the most glacierized mountain range, Sierra Nevada del Cocuy (Florez, 1991; Ceballos et al.,

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2006; Herrera and Ruiz, 2009), shows that: (1) glaciers hardly changed in the 1960s and 1970s; (2) there was a retreat of about $2\% \text{yr}^{-1}$ from the late 1970s to the early 2000s; and (3) a major increase in glacier retreat occurred during the 2000s. For all the Colombian mountain ranges, Morris et al. (2006) and Poveda and Pineda (2009) found that glacier area decreased from 89.3 km^2 in the 1950s to 79 km^2 in the late 1990s and to 43.8 km^2 in the mid-2000s. This represents a total shrinkage of about 51 %, four times greater during the second period. Glaciers in the Cordillera Central of Colombia are frequently located on active volcanoes, and the strong glacier loss was accelerated by several volcanic eruptions in recent years (Huggel et al., 2007), most notably on Nevado del Ruiz in 1985, and on Nevado del Huila where eruptions in 2007 and 2008 resulted in a 30 % loss of glacier surface area in two years.

In Venezuela, Morris et al. (2006) reported that glacier surface area decreased from 2.03 km^2 in 1952 to 0.3 km^2 in 2003 representing a total loss of 87 %.

3.2.5 Summary at the scale of the intertropical Andes

In terms of changes in surface area and length since the mid-20th century (Figs. 4 and 5), the evolution of glaciers in the intertropical Andes can be summarized as follows:

- Between the early 1940s and the early 1960s, information was scarce, but evidence in Peru (Broggi, Uruashraju, Yanamarey), Bolivia (Charquini, Chacaltaya) and Colombia (Sierra Nevada del Cocuy) indicates a moderate retreat ($\sim -0.5\% \text{yr}^{-1}$).
- From the early 1960s to the second half of the 1970s, glacier snout positions remained almost the same.
- A clear change in glacier evolution can be seen in the late 1970s, when the retreat accelerated but stepwise: the first acceleration in the retreat occurred in late 1970s, the second in the mid-1990s, and the third in the early 2000s. These

phases of accelerated retreat were interrupted by 2 to 3 yr with reduced retreat or even short readvances like in Ecuador in 1999–2000 and in 2008–2009.

Glacier shrinkage in the three last decades appears to be unprecedented since the maximum extension of the LIA (mid-17th–early 18th century). In addition, even if glacier retreat is observed everywhere in the intertropical Andes, it should be noted that this retreat (in terms of percentage) is notably more pronounced on small glaciers at low altitudes that do not have a permanent accumulation zone, and which could disappear in the coming years/decades.

3.3 Interannual variability of glacier mass balance

Figure 7 shows the cumulative annual mass balance of the eight glaciers between Colombia and Bolivia for which field measurements have been conducted (Table 1). The longest series available are for Yanamarey Glacier (Cordillera Blanca – Peru, since 1971) and Zongo Glacier (Cordillera Real – Bolivia, since 1973, reconstructed from hydrological data). It should be noted that measurements on Yanamarey Glacier were interrupted several times and to complete the missing data, a linear trend was assumed. Over the last 40 yr, two distinct patterns of loss can be distinguished: (1) small glaciers at low altitudes (<5400 m a.s.l.) such as Yanamarey, Chacaltaya, Charquini Sur and La Conejeras, showed an average trend of $-1.2 \text{ m.w.e. yr}^{-1}$; and (2) glaciers which still have a large accumulation zone at high elevations (>5400 m a.s.l.) such as Zongo, Artesonraju, Antisana 15 and Los Crespos, showed an average trend of $-0.6 \text{ m.w.e. yr}^{-1}$. Taking into account: (1) glacier size and maximum altitude dependency; (2) the distance between the glaciers monitored: 21° in latitude between Zongo and La Conejeras; and (3) distinct hydrological year timing; regional changes in mass balance were homogenous over the whole period. This coherent glacier response suggests common large-scale forcing influencing climatic variability at regional scale (e.g. Francou et al., 2007).

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These long-term trends were superimposed on strong interannual variability. High altitude glaciers experienced major fluctuations between a balanced or even a slightly positive mass balance and deficits reaching more than $-2 \text{ m.w.e. yr}^{-1}$. On the other hand, small glaciers such Chacaltaya, Charquini Sur, and Yanamarey experienced a permanently negative mass balance in recent years. Thus, it can be affirmed that small glaciers with no permanent accumulation zones are very unbalanced and that, with a deficit of around $-1.2 \text{ m.w.e. yr}^{-1}$, they will probably completely disappear in one or two decades (note that this is already the case for Chacaltaya Glacier in Bolivia, which disappeared in 2010).

Figure 8 is a summary of mean annual mass-balance per period combining all available measurements made in Colombia, Ecuador, Peru and Bolivia using different methods (geodetic, hydrological, glaciological and mass balance reconstructions from variations in snowline altitude). The quantity of available data has increased with time from about twenty glaciers in the 1960s–1970s to about thirty glaciers in the 2000s (combining all survey methods). Four important points in this graph are worth emphasizing:

- Although some glaciers sporadically had a positive mass balance, the average signal over the past 50 yr has been permanently negative.
- The late 1970s break point, already discussed with respect to changes in surface area is equally apparent from mean annual mass balance per year, decreasing from $-0.2 \text{ m.w.e. yr}^{-1}$ over the 1964–1975 period to $-0.76 \text{ m.w.e. yr}^{-1}$ over the 1976–2010 period.
- A slight increase in the rate of glacier mass loss occurred during the past two decades.
- Glaciers in the tropical Andes appear to have had more negative mass balances than glaciers monitored worldwide. In addition, tropical glaciers began to shrink at an accelerated rate after 1976, while those located at mid/high latitudes underwent an accelerated retreat about 15 yr later, in the 1990s.

3.4 Synchronicity of the ablation rates throughout the intertropical Andes

Figure 9 shows the cumulative monthly mass balance of five glaciers on which stake emergence was measured monthly, taking into account the snow/ice density. The elevation ranges include the whole glacier surfaces of Chacaltaya, Charquini Sur and La Conejeras glaciers (mostly ablation zones), the lower zone of Antizana 15 Glacier (4800 to 5000 m a.s.l.) and the upper ablation zone of Zongo Glacier (5000 to 5200 m a.s.l.). At a monthly scale, the mass balance in the ablation zone reflects changes in the energy balance (melt energy) and snow accumulation at the glacier surface. In the first decade, i.e. 1991–2001, the patterns remained almost the same: ablation peaked in 1995 and 1997–1998 on the three glaciers monitored at this time, whereas 1993–1994, 1996 and 1999–2000 were more balanced. In the 2001–2006 period, a difference appeared between the inner and outer tropics: the continuous high ablation rates of Antisana 15 Glacier did not appear in Bolivia until 2004. The 2006–2011 period was characterized by an almost balanced situation in both the outer and inner tropics with even a short period of mass gain on La Conejeras Glacier (2007–2008) followed by a marked loss in 2009.

4 Discussion

4.1 Factors controlling seasonal changes in mass balance

Long-term surface energy balance (SEB) field campaigns in Bolivia (Wagnon et al., 1999, 2001; Sicart et al., 2005), Peru (Juen et al., 2007) and Ecuador (Favier et al., 2004a,b) revealed that in the tropics, the variability of SEB in the ablation areas is mostly controlled by net short-wave radiation (S), which is partly compensated by the negative net long-wave radiation budget (L). Due to the low latitude, S is closely linked with cloud cover and surface albedo, which, due to its strong variability and its feedback effect on the melt rate, appears to be a primary variable controlling the amount

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of melt energy at the surface of tropical glaciers. Thus, by causing strong seasonal changes in sky long-wave radiation and solid precipitation, cloud cover controls the seasonal changes in energy fluxes and mass balance on low-latitude high-altitude glaciers (Wagnon et al., 2001; Francou et al., 2003, 2004; Favier et al., 2004a; Sicart et al., 2011). Tropical glaciers are characterized by large vertical mass balance gradients of about $2 \text{ m.w.e.} (100 \text{ m})^{-1}$ in the ablation area (e.g. Kaser et al., 1996; Soruco et al., 2009b), implying a significant contribution of the lowest areas to total ablation. Kuhn (1984) noted the influence of the length of the ablation period. Areal simulation of the energy fluxes at the scale of the Zongo Glacier showed that the frequent changes in snow cover throughout the ablation season were the main explanation for the marked vertical mass balance gradients of tropical glaciers (Sicart et al., 2011). However, the seasonality of precipitation is not the same in the inner and outer tropics. Consequently, the seasonality of melting at the glacier surface also differs.

4.1.1 Specificities of the inner tropics

Concerning Antisana 15 Glacier, Favier et al. (2004a,b) found that at seasonal time scales, mean ablation rates remained almost constant throughout the year, and the inter-annual variability of the mass balance of the glacier was mainly controlled by year-to-year variations in air temperature which determine the snowline altitude (Francou et al., 2004). Glaciers in the inner tropics are thus very sensitive to temperature changes.

Albedo appears to be a major determinant in melting. At a daily time step, a close relation, was shown between albedo and net radiation (Favier et al., 2004b). Changes in albedo go hand in hand with changes in the short-wave radiation balance. Consequently, the frequency and intensity of snowfall, which can occur all year long, play a major role in attenuating the melting processes.

Precipitation and temperature, first during the main precipitation period (between February and May), and second during the secondary maximum (September/October), are therefore crucial for the annual mass balance. Significant snowfall in February–May

clearly reduces the ensuing melting due to the albedo effect. Long periods without snowfall lead to a significant increase in melt rate, particularly in the periods close to the equinox (March/April and September) when potential incoming shortwave radiation is maximum.

5 The high sensitivity of Ecuadorian and Colombian glaciers to climate is closely linked to the absence of temperature seasonality. The 0 °C isotherm consistently oscillates through the ablation zone of the glaciers, and a minor variation in air temperature can influence the melt processes by determining the phase of precipitation in the ablation zone (a temperature increase of 1 °C can move the snow-rain limit about 150 m up
10 the glacier). This explains why the relation between the altitude of the equilibrium line and the freezing level line is a decisive parameter in the glaciers' sensitivity to climatic variations (Kuhn, 1989; Kaser, 2001).

4.1.2 Specificities of the outer tropics

15 In the outer tropics, where liquid precipitation is rare on glaciers, the mass balance is closely related to the total amount and the seasonal distribution of precipitation (Wagnon et al., 2001; Francou et al., 2003; Favier et al., 2004a; Sicart et al., 2005). Three seasons can be distinguished for outer tropical glaciers (Sicart et al., 2011). In the dry season from May to August, melt is low, mainly due to the surface deficit in long-wave radiation due to the low emissivity of the thin cloudless atmosphere at very
20 high altitudes, and not primarily due to sublimation as postulated in earlier studies (e.g. Kaser et al., 1996; Wagnon et al., 1999). During the transition season from September to December, the meltwater discharge progressively increases to reach its highest annual values due to high solar irradiance, with the sun close to zenith, and low glacier albedo. From January to April, the frequent snowfall in the wet season reduces the
25 melt rate, which is nevertheless maintained by high long-wave radiation emitted from convective clouds. The annual mass balance depends on the onset of the wet season, which interrupts the period of high melt caused by solar radiation. Any delay in the

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onset of the wet season causes a very negative mass balance due to reduced snow accumulation and very large ablation.

Finally, Wagnon et al. (2001) showed that the high melt rates measured at the Zongo Glacier weather station during the 1997–1998 El Niño year were mainly due to reduced solid precipitation and associated low albedo. In addition, Sicart et al. (2005) showed that glaciers in the outer tropics are characterized by marked seasonality of long-wave incoming radiation because cloud emission during the wet season considerably increases long-wave clear sky emission from the thin atmosphere. These authors also showed that during the dry season, turbulent fluxes are increased by katabatic winds in a cloudless sky.

4.1.3 Relation between air temperature and ablation on tropical glaciers

Many authors found a high correlation between glacier or snow melt and air temperature (e.g. La Casiniere, 1974; Zuzel and Cox, 1975; Braithwaite, 1981). In both the inner and outer tropics, a significant correlation has been found between mass balance and air temperature at 500 hPa level derived from reanalysis data at a monthly time scale (Francou et al., 2003, 2004).

Few studies have investigated the physical causes of the high correlation between air temperature and ice melt. Paradoxically, net radiation is generally the main incoming energy flux but is poorly correlated with air temperature. However, this correlation makes sense because temperature, as well as melt rate, includes most atmospheric energy fluxes (Kuhn, 1993; Sicart et al., 2008). The turbulent sensible heat flux depends on the temperature gradient between ice and air. The turbulent latent heat flux depends on air humidity, which is limited by saturation humidity, which, in turn, is a function of temperature only. The static stability of the air above a glacier surface increases with increasing air temperature, reducing turbulent convection. Clear-sky long-wave irradiance depends mainly on the humidity and temperature of the near-surface layer of the atmosphere. Furthermore, atmospheric temperature controls the precipitation phase: rain or snow, and the surface albedo can be linked to the air temperature during

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precipitation events. Thus a change in the freezing level can have an impact on the energy balance through changes in the net short-wave radiation budget via the albedo.

4.2 Regional forcing of the mass balance interannual variability: the Pacific Ocean

Figure 10 shows time series of monthly mass balance anomalies and Pacific sea surface temperature anomalies (SSTa). The top graph focuses on the inner tropics and shows the average monthly mass balance of Antisana 15 (1995–2011) and La Conejeras (2006–2011) glaciers with the SSTa of the Niño 3.4 region. The bottom graph focuses on the outer tropics, with the average monthly mass balance of Zongo (1991–2011), Chacaltaya (1991–2005) and Charquini Sur glaciers (2002–2011) and the SSTa of the Niño 1 + 2 region.

In Ecuador, as shown by Francou et al. (2004) and Vuille et al. (2008a), the two opposite phases of ENSO explain the highly contrasted situations on the Antisana 15 Glacier. Since the SSTa peak in the Central Pacific during the boreal winter (November–February) and the atmospheric response to ENSO over the Ecuadorian Andes is delayed by three months, year-to-year variability of the mass balance is maximal from February to May. During warm ENSO phases, increasing temperatures favor precipitation at the melting point up to 5100–5200 m a.s.l., which, together with the slight deficit in precipitation and cloudiness, explains the unvarying low values of the albedo and the high melt rates (Favier et al., 2004a,b). In contrast, the cold ENSO phase brings cooler temperatures, higher snowfall and increased cloudiness, which, for long periods, prevent albedo from dropping below the typical values of the fresh snow (0.8) and decreases available energy for melt. To a lesser extent, stronger winds during austral winter boost sublimation and reduce melting.

In Colombia, the impacts of ENSO on glaciers are similar to those in Ecuador. It has been observed that monthly mass balance was up to three and a half times more negative during El Niño events than in an average month. On the other hand, the 2007/08 La Niña event resulted in a positive mass balance on La Conejeras Glacier.

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In Bolivia, variations in the interannual glacier mass balance are also to a large extent controlled by SSTa in the tropical Pacific (Francou and Ribstein, 1995; Francou et al., 2003; Vuille et al., 2008a). During the ENSO warm phase (El Niño), precipitation decreases by 10–30 % and dry periods occur more frequently during austral summer (Vuille et al., 2000). This situation increases incoming solar radiation, reduces snow accumulation and decreases albedo on the glacier surface (Wagnon et al., 2001). On average, the near-surface summer temperature is 0.7 °C–1.3 °C higher during El Niño than during La Niña (Vuille et al., 2000), enhancing sensible heat flux to the glacier surface. During the relatively wet and cold La Niña periods, opposite conditions prevail, which can lead to near equilibrium mass balance. However, as can be seen on the lower graph in Fig. 10, the response of mass balance to the SSTa forcing is not systematic, for example over the 1992–1995 and 2001–2005 periods. Although the positive mass balance anomaly in the 1992–95 period has been attributed to the cooling effect of the Pinatubo eruption in June 1991 (Francou et al., 2003), the situation that occurred between 2001 and 2005 is still being analyzed. Nevertheless, new characteristics observed in ENSO variability (Central Pacific/Eastern Pacific or “Modoki” ENSO) could explain the slight differences in the response of glaciers in this region to the ENSO phenomenon, particularly for the outer tropics, this point will be the focus of a forthcoming paper by Francou et al. Finally, ENSO influence on Sajama Volcano glaciers has also been highlighted by Arnaud et al. (2001) showing that the snowline elevation is related primarily to precipitation and to a lesser degree to temperature.

Concerning the Cordillera Blanca in Peru, the mechanisms linking ENSO and glacier mass balance are similar to those in Bolivia, with the SSTa exerting the prevailing large-scale control on interannual mass balance variations. Typically, El Niño events result in negative mass balance anomalies, and La Niña in above average signals. However, these teleconnections are spatially unstable and ENSO events with reversed effects on glacier mass balance have been observed (Vuille et al., 2008b).

During periods when ENSO is near neutral conditions, other atmospheric forcing, such as variations in South American monsoon intensity and duration, the so-called

“surazos”, which cause precipitation during the dry period due to Southern Hemisphere mid-latitude disturbances tracking abnormally north of their usual path (Ronchail, 1995) and the South-Atlantic convergence zone, also have an impact on interannual mass balance variability.

4.3 Causes of glacier retreat since the LIA maximum

The formation of moraines at a distance of about 800 to 1000 m from the present glacier snout during the period of maximum extent (PME) of the LIA means that the specific mass balance was very positive, generating a significant transfer of ice downstream from the glacier to offset increasing ablation at low altitude. From sensitivity studies, Rabatel et al. (2006) suggested that conditions may have been wetter during the LIA, thus increasing accumulation rates, and, in conjunction with lower temperatures, leading to a decrease in the freezing level. This hypothesis is consistent with other proxies, one based on ice core evidence (Fig. 2 lower panel). For example, in several ice cores, Thompson et al. (2006) and Vimeux et al. (2009) noted a marked centennial-scale decrease in the $\delta^{18}\text{O}$ of the snow/ice between the late 16th and early 19th century. The minimum $\delta^{18}\text{O}$ content between ~ 1620 AD and ~ 1730 AD can be considered to be related to increasing convective activity during the PME (Vimeux et al., 2009). New $\delta^{18}\text{O}$ records from Andean speleothems and lake records also confirm that, in this region, the LIA period must have been wet (Bird et al., 2011). Pollen analyses from the Sajama ice core (Liu et al., 2005), along with dendroclimatological studies in the same area of the Bolivian Altiplano (Morales et al., 2012), are also in agreement with wetter conditions during the PME of the LIA.

Quantitatively, the application of simple climate/glacier models (Polissar et al., 2006; Rabatel et al., 2008a; Jomelli et al., 2009) highlights several points:

- In Venezuela, for the period AD 1250–1820, average air temperature may have been $3.2 \pm 1.4^\circ\text{C}$ cooler, and precipitation about 22 % higher than at present.

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- In Ecuador, air temperature may have been 0.8 °C to 1.1 °C below today's values, and a 25 % to 35 % increase in accumulation appears to have occurred in the 18th century.
- In Bolivia, the PME of the LIA could be the result of a decrease in temperature of 1.1 °C to 1.2 °C, and a 20 % to 30 % increase in accumulation.
- In Colombia, the air temperature during the PME of the LIA was estimated to be 1.2 °C to 1.5 °C lower than at the turn of the 21st century (Baumann, 2006).

A major difference between tropical and mid-latitude glaciers is that the tropical glaciers began to retreat just after 1740–1750 AD, a long trend of recession which may have been associated with drier conditions. Indeed, drier conditions are indicated by the analysis of paleo-lake levels on the Peruviano-Bolivian Altiplano (Chepstow-Lusty et al., 2003). The shift to drier conditions between the late 18th and early 19th centuries is also apparent in pollen analyses of the Sajama ice core (Liu et al., 2005) and net accumulation from Quelccaya ice core (Thompson et al., 1985). However, the recession was probably not continuous since distinct moraines were deposited between the PME and the late 19th–early 20th centuries, indicative of small glacial advances, although those never reached a magnitude as great as those in the PME. It was the case during the first half of the 19th century in Bolivia and Peru as well (Rabatel et al., 2006, 2008a; Jomelli et al., 2009) with two small glacier advances (moraine stages dated from ~1800 AD and ~1860 AD) which could be related to relatively wetter conditions.

The last decades of the 19th century were characterized by a substantial glacier retreat at a regional scale which could be due to dry conditions as documented in climate proxies and the first instrumental measurements (Kraus, 1955; Torrence and Webster, 1999).

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4.4 Causes of the accelerated retreat in the last 30 yr

4.4.1 Climate changes in recent decades

Recently, Vuille et al. (2008a) presented a review of climate changes in the 20th century along the tropical Andes. These authors reported that:

- Precipitation changes are difficult to document because of the lack of high-quality long-term precipitation records. Moreover, the variability at the decadal time scale is higher than the multidecadal trend, partly due to ENSO effects. However, studies showed an increasing trend in precipitation after the mid-20th century (both at an annual scale and during the wet season) north of 11° S, i.e. in Ecuador and Northern/Central Peru. Inversely, in Southern Peru and the Bolivian Altiplano, most weather stations indicated a decreasing trend (Vuille et al., 2003; Haylock et al., 2006).
- Changes in humidity are very hard to quantify as, in the Andes, no long-term continuous records exist. However, based on CRU05 data, Vuille et al. (2003) found a significant increase in relative humidity for the 1950–1995 period ranging from 0.5%decade⁻¹ (in Bolivia) to more than 2.5%/decade (in Ecuador). Similarly, based on NCEP reanalysis data, Salzmann et al. (2012) found a significant increasing trend in specific humidity in the Southern Peruvian Altiplano over the past 50 yr.
- During the 1974–2005 period, outgoing long-wave radiation (OLR) decreased in the inner tropics, suggesting an increase in convective activity and cloud cover, whereas in the outer tropics, the opposite trend is documented (Vuille et al., 2003). This pattern is consistent with precipitation trends in the same period.
- Temperature is by far the best documented climate parameter. Based on 279 weather stations located between 1° N and 23° S, Vuille et al. (2008a) showed that near-surface air temperature increased significantly (by 0.10°C decade⁻¹) in

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the last 70 yr, which represents an overall temperature increase of 0.68°C since 1939. These findings confirm results obtained by other authors in Peru (Mark and Seltzer, 2005), Bolivia and Northern Chile (Vuille et al., 2000) and Ecuador (Quintana-Gomez, 2000; Villacis, 2008) and along the entire tropical Andes from Ecuador to Northern Chile (Vuille and Bradley, 2000), all of whom reported a significant warming trend and a reduced daily temperature range (difference between daily minimum and maximum temperatures). Consistent with this increase in temperature, Gilbert et al. (2010) showed from englacial temperature measurements in a 138 m deep borehole drilled near the summit of Illimani (6340 m a.s.l., Bolivia) that a warming trend can also be identified along the temperature profile at very high altitudes. These authors quantified a mean rise in atmospheric temperature of $1.1 \pm 0.2^{\circ}\text{C}$ over the 20th century. It should be noted that this increase in temperature is the only evidence recorded in the Andes at the elevation of glaciers, as most weather stations are located below 4000 m a.s.l.

Figure 11 shows changes in freezing level height in the Andean Cordillera documented based on NCEP-NCAR reanalysis data. Freezing level height was computed using monthly temperatures and geopotential height and plotted as a 12-month running mean for the 1955–2011 period at three sites (Antisana in Ecuador, Cordillera Blanca in Peru, and Cordillera Real in Bolivia) using the elevation range of the ablation zone at each site as a backdrop. For each site, the grid cell including the site was selected. In the inner tropics (Antisana in Ecuador), during the 1955–2011 period, the ablation zone extended down to the freezing level, thus explaining the year-round strong ablation rates. In the outer tropics of Peru ($\sim 9^{\circ}\text{S}$) and Bolivia ($\sim 16^{\circ}\text{S}$), except during strong El Niño events, the ablation zone tended to be located above the annual mean freezing line during the first half of the study period. But the recent marked increase in freezing levels led to a situation in which the ablation zones of the Cordillera Blanca and today even of the Cordillera Real are mostly located within the range of the annual mean freezing level.

Quantitatively, the freezing level height has increased by about 60 m and 160 m over the last five and a half decades in the inner and outer tropics, respectively. This increase can be partially traced back to the increase in the tropical Pacific SST (Diaz et al., 2003; Bradley et al., 2009).

Figure 12 shows cumulative temperature (monthly mean values of NCEP-NCAR re-analysis data) at the elevation of the glacier snout for the same three locations as in Fig. 11. At Antisana and in the Cordillera Blanca, the temperature was very close to 0 °C at the glacier snout up to the late 1970s, when temperatures started to rise and cumulative temperature became positive. Temperatures have continued to increase ever since, meaning that, except for short intervals associated with the cold phase of ENSO, they have remained positive. For example, in 1997/1998 El Niño led to marked warming and in 1999/2000 La Niña led to cooling (Antisana) or at least stabilization of the cumulative temperature (Cordillera Blanca), but this event was short lived. The situation in the Cordillera Real (Bolivia) appears to be a little different, because in the outer tropics glaciers are located in an area with a dryer climate and therefore at higher elevations relative to the freezing line. Hence from 1955 to the mid 1990s, temperatures at the Zongo Glacier snout were mainly below freezing and the cumulative temperature was consequently negative. However, since the early 2000s, the temperature has reached freezing point and as a result the cumulative temperature curve flattened out and even started to rise in the past two years.

4.4.2 Linking current climate change and glacier evolution in the tropical Andes

The higher SST of the tropical Pacific Ocean off the coast of South American observed after the 1976 Pacific climate shift, most likely helped to accelerate glacier retreat throughout the tropical Andes. This strong signal is superimposed on higher frequency, large-scale atmospheric events. The Pinatubo eruption, an event of this type, occurred in June 1991 and for several months affected the glacier mass balance through a cooling effect of the volcanic sulfate aerosols in the stratosphere hence interrupting the long El Niño period (1990–1995), and causing the only slightly positive

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mass balance in the entire decade on Chacaltaya Glacier (Francou et al., 2003). Thus, we can assume that the higher frequency and the change in the spatio-temporal occurrence of El Niño since the late 1970s, together with a warming troposphere over the tropical Andes, explain much of the recent dramatic shrinkage of glaciers in this part of the world.

Finally it is interesting to note that the beginning of the accelerated retreat of tropical glaciers occurred at the same time as a major increase in the global temperature curve after 1976 (Trenberth et al., 2007) that incorporates the warming of the tropical Pacific and other tropical regions. Glaciers all around the Pacific and Indian oceans underwent accelerated retreat since 1976 (with the exception of glaciers in New Zealand until the early 2000s, which are also influenced by ENSO, but in the opposite way). In the Northern Hemisphere, from Alaska to Northern Russia, and throughout Europe, the main forcing is the North Atlantic Oscillation, resulting in: (1) a slight time lag in the beginning of accelerated retreat period (late 1980s/early 1990s); and (2) distinct mechanisms of variability at a decadal scale (e.g. Francou and Vincent, 2007).

4.5 Possible future changes in tropical glaciers in the Andes: results of modeling

Using results from eight different general circulation models used in the 4th assessment of the IPCC, and CO₂ levels from scenario A2, Bradley et al. (2006) showed that projected changes in mean annual free-air temperatures between (1990 to 1999) and (2090 to 2099) along the tropical Andes at an elevation higher than 4000 m a.s.l. will increase by +4 °C to +5 °C. The maximum temperature increase is predicted to occur in the high mountains of Ecuador, Peru and Bolivia (Bradley et al., 2006). Urrutia and Vuille (2009), using a high-resolution regional climate model, came to similar conclusions with respect to changes in near-surface temperature. To test the response of glaciers to changes in air temperature, Lejeune (2009) performed a sensitivity analysis of glacier mass balance and equilibrium-line altitude by applying the CROCUS snow model to the Zongo Glacier in two contrasted wet seasons (2004–2005 and

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2005–2006). The results of this analysis showed that for a 1°C increase in air temperature, the increase in ELA would be $150 \pm 30\text{m}$. With such a result and assuming that changes in ELA are linearly proportional to changes in temperature, the above mentioned projected changes in air temperature ($+4^{\circ}\text{C}$ to $+5^{\circ}\text{C}$) simulated at the elevation of the glaciers for the end of the 21st century would result in an ELA increase on the order of 480 to 900 m. With ELA_0 currently located at $\sim 5150\text{m a.s.l.}$ (Rabatel et al., 2012), such an increase would locate the ELA between 5630 and 6050 m a.s.l. at the end of the 21st century, i.e. in the upper reaches of the Zongo Glacier, with a subsequent drastic reduction in its surface area. If extrapolated to other glaciers in the Cordillera Real, such an increase in the ELA would cause the disappearance of most glaciers in this massif. However, these results are preliminary, and they need to be supplemented and expanded by the analysis of the sensitivity of mass balance and ELA to other meteorological parameters (precipitation, humidity, radiation) at longer time scales.

5 Summary and concluding remarks

This review of glacier changes over the last 50 yr and two decades of constant field observations of some representative glaciers in the tropical Andes enabled us to highlight the following conclusions:

- Consistent with most mountain glaciers worldwide, glaciers in the tropical Andes have been retreating at an increasing rate since the late 1970s. Although sporadic positive mass balances have been observed on some glaciers, the average mass balance has been permanently negative over the past 50 yr. The mean mass balance deficits of the tropical Andes rank among the most negative observed in the world.
- The magnitude of glacier retreat is directly related to the size of the glacier. Large glaciers that still have an accumulation zone above 5400 m a.s.l. have typically lost

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–0.6 m.w.e. yr⁻¹ over the last three and a half decades. Whereas smaller glaciers
whith no accumulation zone have shrunk at an average rate of –1.2 m.w.e. yr⁻¹,
i.e. at twice the rate of the former. In either case, the current retreat appears to be
unprecedented since the LIA maximum, i.e. since the second half of the 17th century
and the early 18th century.

- Interannual variability of mass balance is high, with negative mass balance oc-
curring much more frequently than periods with near-equilibrium or positive mass
balances, which occurred in only a few years. The variability of the tropical Pa-
cific SST is the main factor controlling the variability of the mass balance at the
interannual to decadal time scale.
- In the very high-altitude mountains of the tropical Andes, radiation fluxes, and
more specifically the net short-wave radiation budget, control the energy balance
at the glacier surface during the melt season. Consequently, through its effect on
albedo, solid precipitation controls seasonal changes in energy fluxes and hence
in the mass balance of these glaciers. Because precipitation has not displayed
a significant and spatially coherent trend in the tropical Andes since the middle of
the 20th century (unlike temperature, which has increased at the significant rate
of 0.10 °C decade⁻¹ in the last 70 yr), we assume that atmospheric warming is
the main factor explaining the current glacier recession. However, a large propor-
tion of atmospheric warming is transmitted to a glacier through precipitation via
a change in phase. This finding was confirmed by observations made during El
Niño and La Niña periods, when due to a change in frequency and/or in precipi-
tation amounts, a change of phase determines albedo. Energy balance measure-
ments revealed that the direct effect of atmospheric temperature via the sensible
heat flux plays a minor role in ice melt in a tropical environment. On the other
hand, specific humidity (which has also been increasing in the tropical Andes)
might also play a role in glacier shrinkage by transferring energy from sublimation
to melting, but this effect has not yet been quantified.

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– Given the current climatic context, and the future changes in atmospheric temperature projected by both global and regional climate models, many glaciers in the tropical Andes could disappear during the 21st century, and those located below 5400 m a.s.l. are the most vulnerable.

5 – The ongoing recession of Andean glaciers will become increasingly problematic for regions depending on water resources supplied by glacierized mountain catchments, particularly in Peru. This issue was not specifically discussed here, as it is beyond the scope of the present review, but it has been highlighted in several recent studies (e.g. Bradley et al., 2006; Villacis, 2008; Kaser et al., 2010).

10 Aside from continuing and expanding the field monitoring programs, it is therefore of critical importance, to focus on glacio-hydrological modeling and analysis in order to provide policy- and decision-makers with adequate and useful information on how to manage water resources in regions with rapidly shrinking glaciated areas.

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Table 1. Characteristics of the glaciers monitored and date of the beginning of the observations.

	Zongo	Chacaltaya	Charquini Sur	Artesonraju	Yanamarey	Antisana 15	Los Crespos	La Conejeras ^a
Location	16°15' S 68°10' W	16°21' S 68°07' W	16°17' S 68°09' W	8°57' S 77°27' W	9°39' S 77°16' W	0°29' S 78°9' W	0°29' S 78°9' W	4°48' N 75°22' W
Surface area (km ²)	1.94	–	0.32	5.39 ^b	0.60 ^b	0.63	1.71	0.22
Max. elevation (m a.s.l.)	6000	5396	5300	5979	5200	5760	5760	4960
Min. elevation (m a.s.l.)	4900	–	4985	4685	4725	4780	4680	4720
Aspect	SE	S	S	WSW	SW	NW	SW	NW
First year of mass-balance survey	1991 ^c	1991–2009 ^c	2002 ^c	2003 ^c	1971 ^c	1995 ^c	2005 ^c	2006 ^d

^a La Conerejas Glacier is located on Nevado Santa Isabel (Fig. 1).

^b Surface area in 2006.

^c LMI Great Ice.

^d IDEAM.

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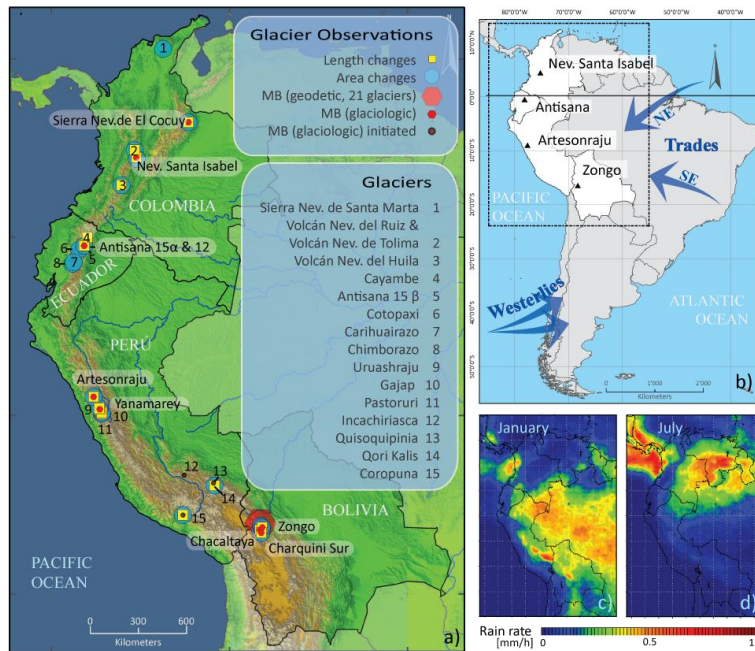


Fig. 1. (a) Glaciers monitored in the tropical Andes. Glaciers with continuous mass balance series (small red hexagons) are labelled. For these glaciers length (yellow cube) and area (blue circle) records also exist. The large red hexagon depicts a sample of 21 glaciers in the Cordillera Real, Bolivia, for which mass balance reconstructions are available from 1963 to 2006 (Soruco et al., 2009a). Other glaciers whose changes in length and/or in area are monitored are numbered. “MB initiated” indicates glaciers with mass balance measurements starting in 2008 (Incachiriasca), 2009 (Coropuna) and 2010 (Quisoquipinia). **(b)** General atmospheric circulation over South America. The dotted frame shows the extent of the precipitation maps in Fig. 1c and d. **(c)** and **(d)** Mean hourly precipitation intensity (mm hr^{-1}) in January **(c)** and July **(d)**, respectively, from 1998 to 2010 based on TRMM (Tropical Rainfall Measurement Mission) Product 3B43 V6.

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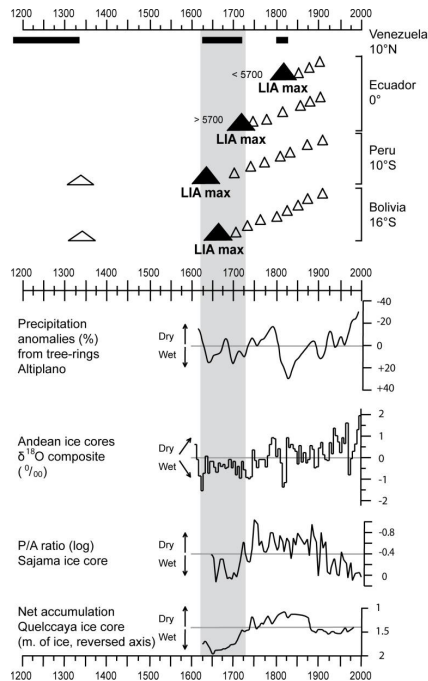


Fig. 2. Comparison of moraine stages dated by lichenometry (triangles) and glacier advances evidenced from lake sediments (Venezuela) with different proxies of climate variations (wet/dry periods) in recent centuries. The position of the triangles qualitatively represents the position of the moraines along a schematic proglacial margin for glaciers in Ecuador (glacier with a summit above or below 5700 m a.s.l.), Peru and Bolivia. Note that the moraine stages and mainly the PME (black triangles) match a period of increased accumulation. The *P/A* ratio in the Sajama ice core (Liu et al., 2005) represents the relative change in abundance of two pollen species (*Poaceae* and *Asteraceae*) and is used as a proxy of moisture on the Altiplano. The precipitation anomaly evidenced in tree rings comes from Morales et al. (2012), and data from ice cores come from Thompson et al. (1985, 2006).

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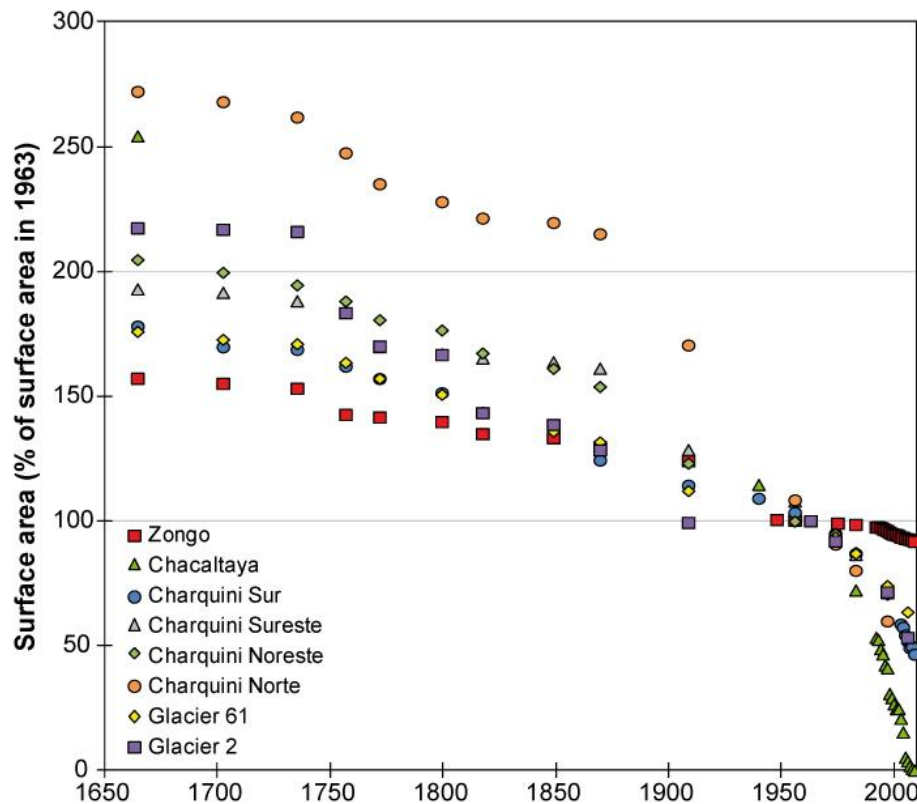


Fig. 3. Changes in the surface area of eight glaciers in the Cordillera Real, Bolivia, since the LIA maximum, reconstructed from moraine stages (LIA maximum and before 1940) and aerial photographs (1940 and after), for the year 1963.

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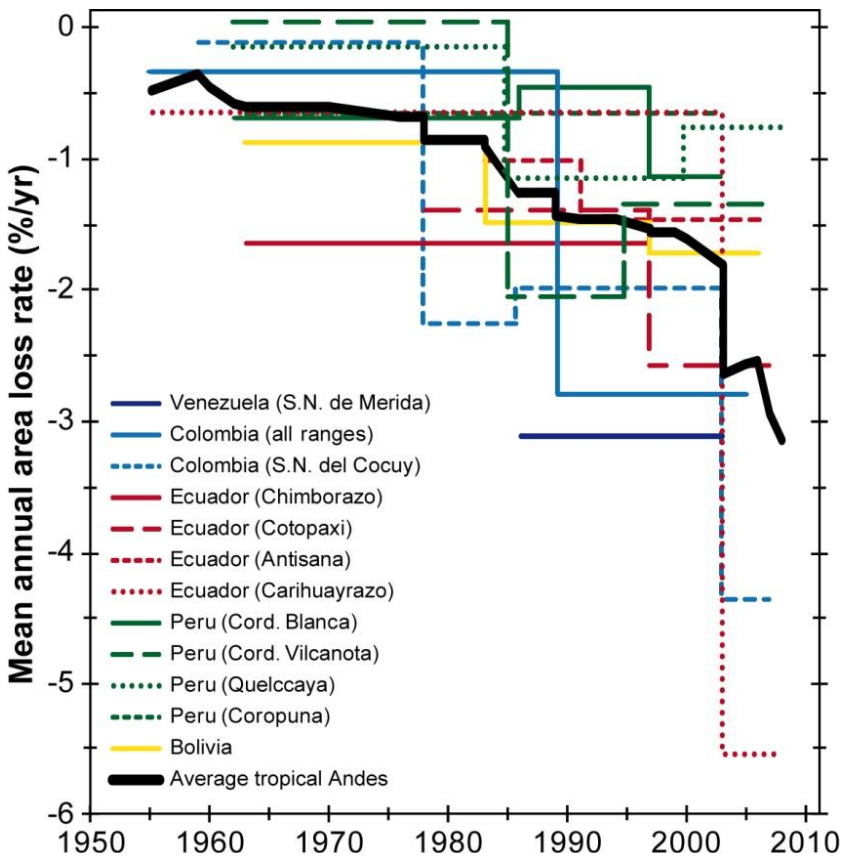


Fig. 4. Compilation of mean annual area loss rate between Venezuela and Bolivia computed from maps, aerial photographs, satellite images and direct topographical measurements. Sources are given in the text. Note that the average is computed from a varying number of values depending on the period concerned because of fewer data were available for the first decades of the study period.

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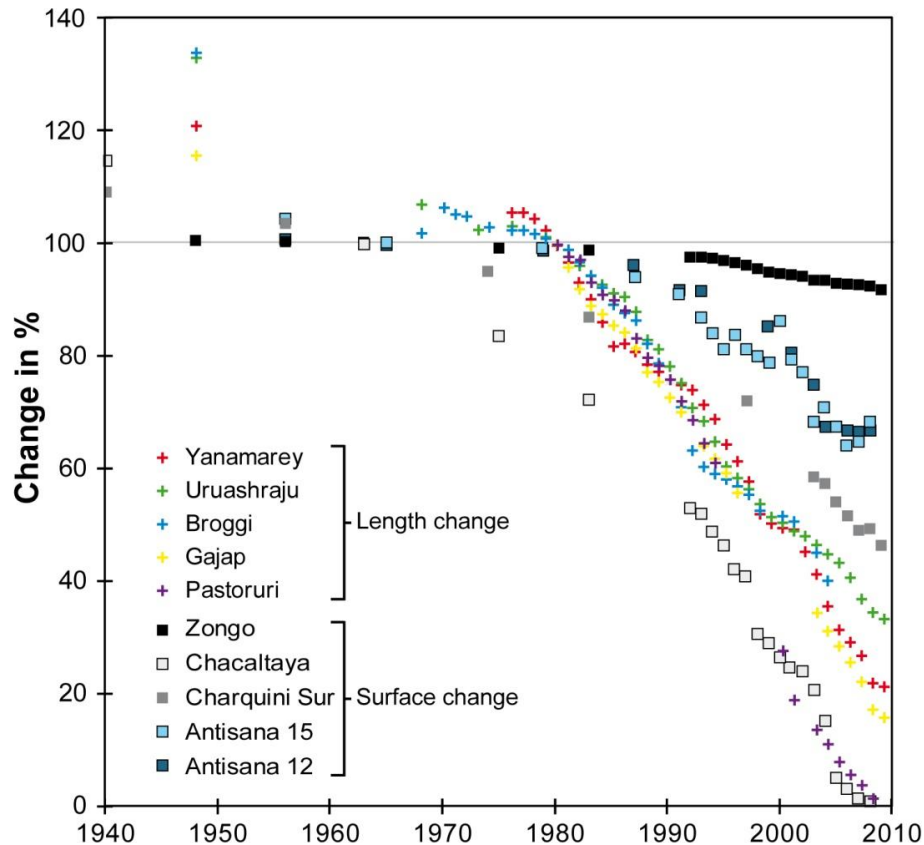


Fig. 5. Changes in surface area and length of 10 glaciers in Ecuador, Peru and Bolivia. Changes in length in Peru come from field measurements and are plotted as changes in cumulative length compared with 1980. Changes in surface area in Bolivia and Ecuador were computed from aerial photographs and from direct measurements since the early 1990s and are shown as cumulative changes in surface area compared with 1963.

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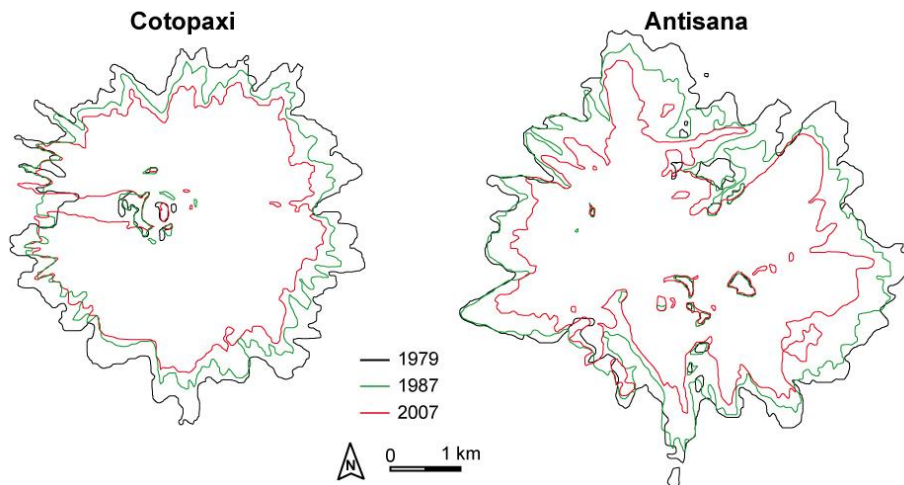


Fig. 6. Glacier outlines for Cotopaxi and Antisana volcanoes for 1979, 1987 and 2007, computed from satellite images.

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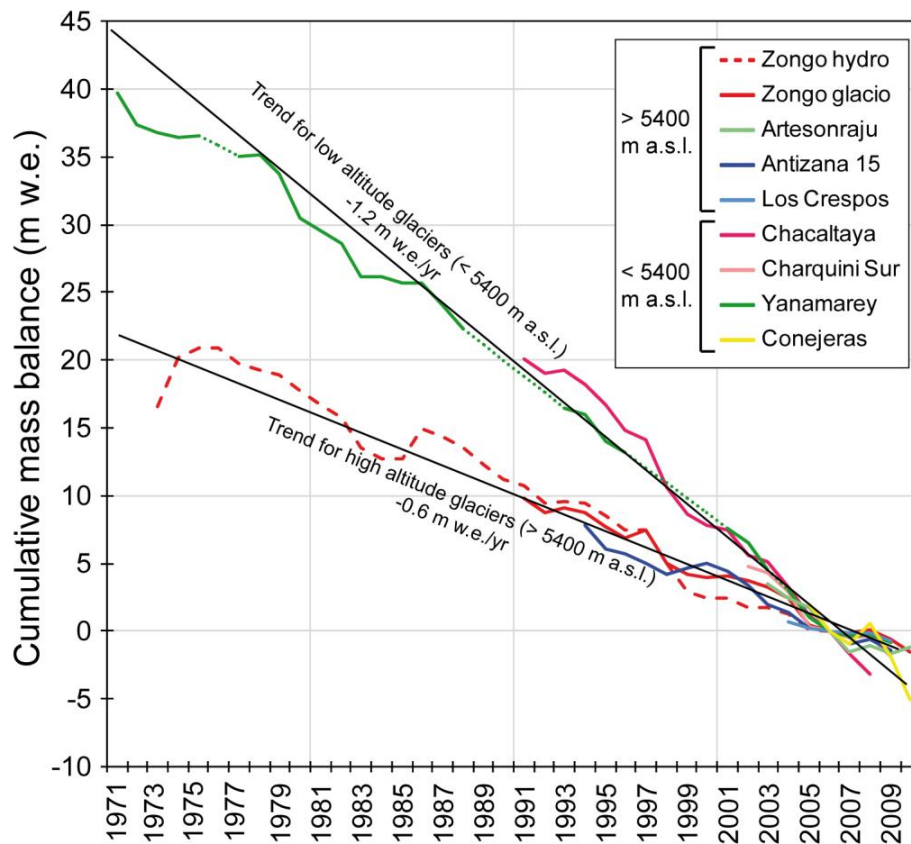


Fig. 7. Cumulative annual mass balance series computed for eight glaciers in the tropical Andes. 2006 was chosen as the common reference.

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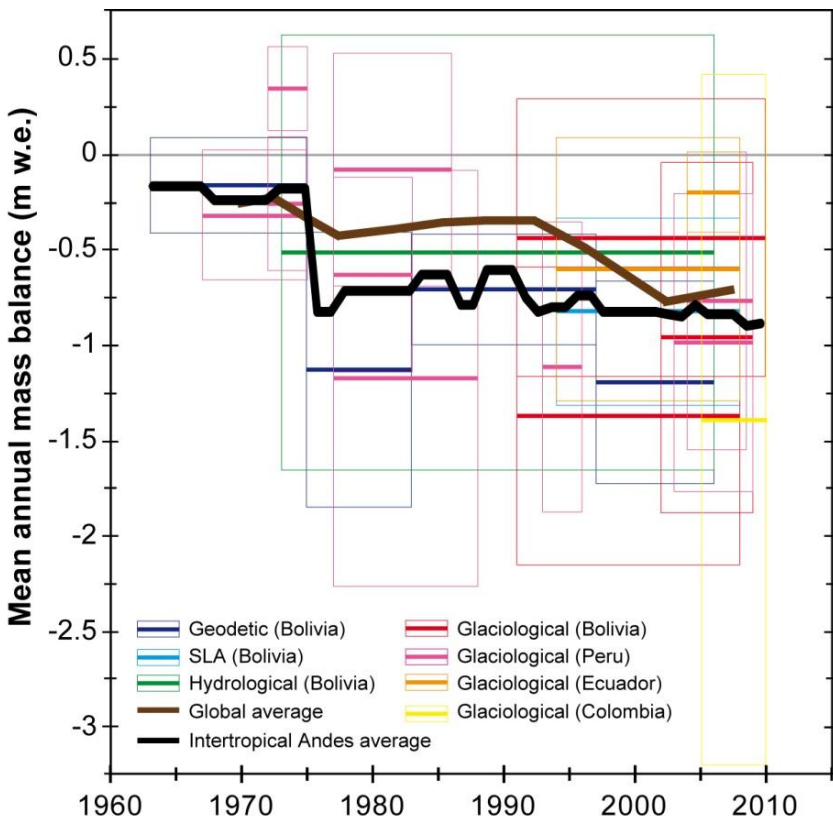


Fig. 8. Compilation of all available measured rates of change in mass balance in the intertropical Andes. Glaciological and hydrological measurements are made annually; geodetic measurements are pluriannual and result from sporadic photogrammetric surveys. SLA represents the reconstruction of mass balance using variations in snowline altitude. Each budget is drawn as a thick horizontal line contained in a ± 1 standard deviation box. The tropical Andes average was computed from available data. The global average comes from Cogley et al. (2012).

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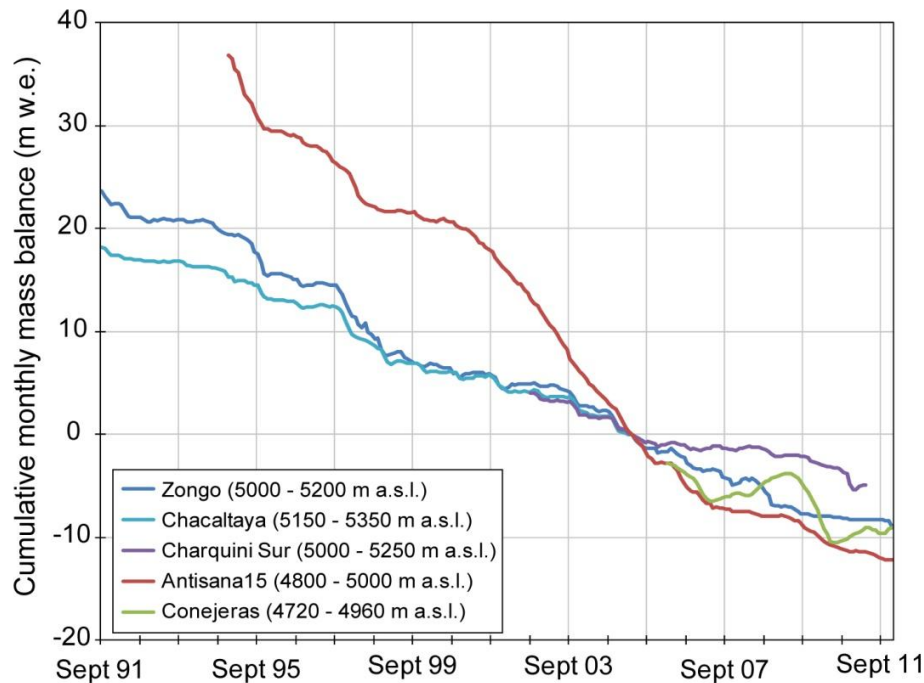


Fig. 9. Cumulative monthly mass balance for five glaciers in the tropical Andes where the measurements were made at this time scale (the reference time for the cumulative time series is April 2005, except for Conejeras Glacier where measurements began in March 2006). Note that for Zongo and Antisana 15 glaciers, only the results of the ablation zone are plotted. Monthly mass balance measurements on Chacaltaya Glacier were stopped in September 2005 because the glacier was too small.

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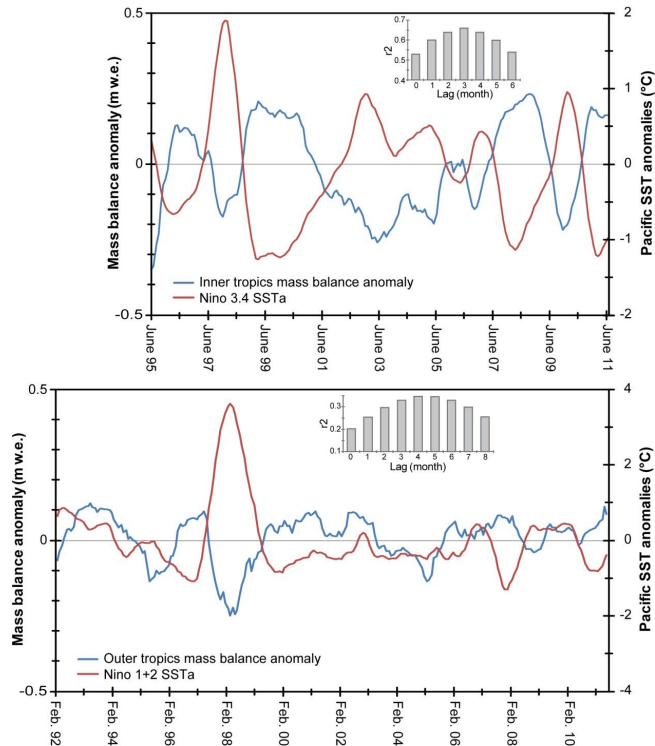


Fig. 10. Upper graph: time series of monthly mass balance anomalies (m w.e.) for the inner tropics (mean of Antisana 15 and La Conejeras glaciers) and Niño 3.4 SSTa (°C) between June 1995 and August 2011. Both time series were smoothed with a 12-month averaging filter. Mass balance anomalies lag SSTa by 3 months. Vertical bar plot (inset) shows the correlation between mass balance anomalies and the Niño 3.4 index, with the Niño 3.4 index leading mass balance anomalies by between 0 and 6 months. Lower graph: the same but for the outer tropics (mean of Zongo, Chacaltaya and Charquini Sur glaciers) and Niño 1 + 2 SSTa. The best correlation between both series was with a 4-month lag (see the vertical bar plot inset).

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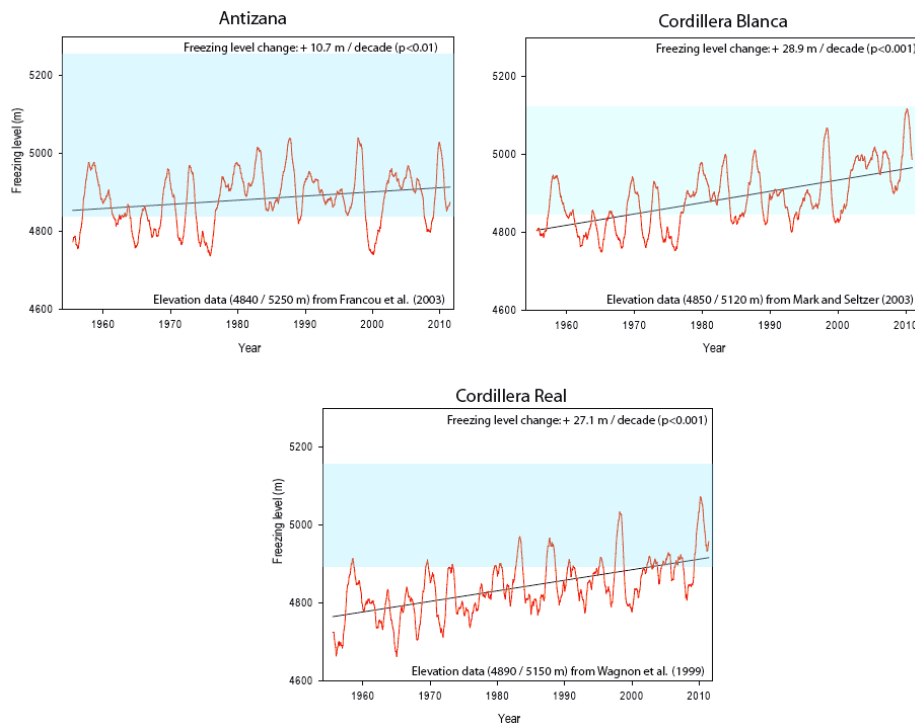


Fig. 11. Changes in freezing level height in the Andean Cordillera computed from NCEP-NCAR reanalysis data (1955–2011) for three sites (Antisana in Ecuador, Cordillera Blanca in Peru, and Cordillera Real in Bolivia) in parallel with a range of elevations from the lowest glacier snouts to the mean elevation of glaciers at each site (blue shaded area).

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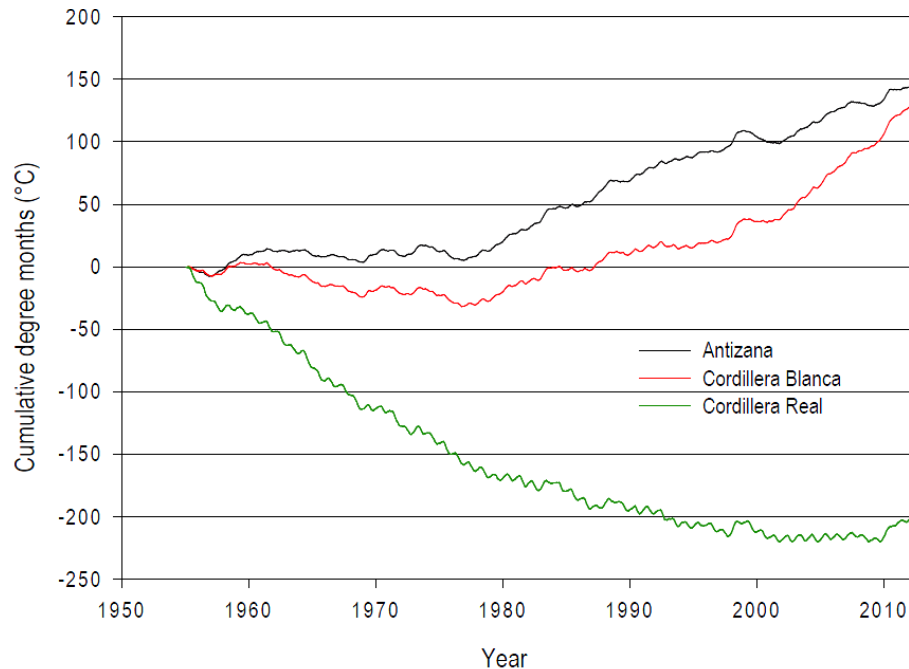


Fig. 12. Cumulative degree months (NCEP-NCAR temperature reanalysis data) at glacier snouts for the 1955–2011 period at three locations (Antisana in Ecuador, Cordillera Blanca in Peru, and Cordillera Real in Bolivia).

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