Climate change and its relation to the fluctuation in glacier mass balance in the Cordillera Blanca, Peru: a review

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ABSTRACT

This review article describes the main probable causes of glacier fluctuations in the Cordillera Blanca since the end of the Little Ice Age. The Cordillera Blanca glaciers reached their last maximum extent during the Little Ice Age and have been retreating since the second half of the 19th century. The progressive glacier recession continued throughout the 20th century but was interrupted several times by periods of glacier advances. The last of these advances took place at the end of the 20th century. However, glacier advances were too short to compensate for the total glacier loss. The major phases of advance and retreat of glacier fluctuations have been well documented and climate changes seem to be their most probable drivers. However, interpreting the climatic forcing that causes such a change in the mass balance remains problematic. The response of tropical glaciers to climatic forcing is complex and glacier recession is likely to involve other components of the energy balance in thermally homogenous areas.

1. Introduction

Mountain Holocene glacier fluctuations have been considered as proxies of climate change for over a century. Studies in all of the mountain regions from the poles to the equator have revealed a multitude of high-frequency glacier fluctuations, mainly related to local-regional climate variability (Orombelli 2011). Moreover, the almost worldwide increase in air temperatures during the last century has caused a reduction in the extent and volume of ice in the majority of the world's mountain areas (Colombo et al. 2016; López-Moreno et al. 2017; Oerlemans 2005). However, glaciated mountain regions are among the world's most sensitive and vulnerable areas to climate change (Beniston 2003; Gardner, Dekens 2007). The climate has a significant influence on the mass balance of mountain glaciers, and the IPCC reports with "high confidence" that warming has led both to a reduction in snow and ice masses and to the formation of moraine-dammed glacial lakes that can "have a high potential for glacial lake outburst floods (GLOFs)" (Rosenzweig et al. 2007).

The mass balance gradient of a glacier is a key control in factors such as the glacier's response time. A glacier's mass balance gradient is critically determined by the climatic regime in which it sits. Globally, mountain glaciers have been retreating since the middle of the 19th century after the end of the Little Ice Age (LIA) both on a global and local scale (Fraser 2012; Giaccone et al. 2015; Hastenrath, Ames 1995). This long-term melting was interrupted by advancing several times in the past, but this was too short and failed to amount to the total loss (Kaser, Georges 1999; Georges 2004). Glaciers at relatively low latitudes may be sustained by very high precipitation. They will therefore have a greater mass balance gradient (more accumulation, more ablation). These tropical glaciers may have a shorter response time and higher climate sensitivity than cold, polar glaciers that receive little accumulation but also have correspondingly low ablation (Francou et al. 2003; Kaser 1999; Wagnon et al. 1999). The retreat is rapid and the recession accelerated in the late 20th century.

The Cordillera Blanca has the greatest concentration of tropical glaciers in the world and the glacier shrinkage has been well documented and it is the subject of a systematic glacier inventory and mapping (Racoviteanu et al. 2008; Mark, Seltzer 2005; Silverio, Jaquet 2005; Kaser, Georges 1997; Kaser et al. 1996; Hastenrath, Ames 1995). Georges (Georges 2004) estimated that the glacier covered area in the Cordillera Blanca decreased from 800–850 km^2 in 1930 to 600 km^2 at the end of the 20th century. Although, progressive glacier recession in this area is well known, interpreting the climatic forcing causing such a change in the mass balance remains problematic (Mark, Seltzer 2005). The response of tropical glaciers to climatic forcing is complex and glacier recession is likely to feature many components of the energy balance in the thermally homogenous area (Kaser, Osmaston 2002). While temperature may be strongly correlated to glacier recession, it integrates many closely interconnected surface energy-mass fluxes and humidity affecting mass balance through altered all-wave radiation, which actually controls glacier mass balance (Francou et al. 2003; Vuille et al. 2003).

One of the objectives of this paper is to examine the relevant relationship between climate change and mass balance in the Cordillera Blanca. It has also provided a basis for several studies on natural hazard evaluation, which are closely related to climate changes and glacial retreat and the consequent formation of new lakes in over-excavated basins (Bury et al. 2011; Carey et al. 2012; Huggel et al. 2012; Emmer et al. 2014; Vilímek et al. 2015). As hydrological (runoff and glacier meltwater) and geomorphological (glacier deposits) processes in watersheds affected by recent deglaciation are very active, and the landscapes are very often carved in very unstable terrain (Benn, Evans 2010), glacial lake outburst floods (GLOFs) pose a great risk to populations in their drainage areas (Carrivick, Tweed 2013). The Andes, in particular the Cordillera Blanca Peruvian mountains, are often a dramatic showcase for these hazards as reported in many works (Kaser et al. 2003; Vuille et al. 2003; Mark, Seltzer 2005; Vuille et al. 2008b) and also other mountain areas including the Cordillera Huayhuash (McFadden et al. 2011), Cordillera (Vilcanota et al. 2013), Coropuna (Racoviteanu et al. 2007) and Huaytapallana (López-Moreno et al. 2014).

2. Study area

The Cordillera Blanca is located between 8°S and 10°S in the Peruvian Andes, which are the most glaciated area in the tropics (Figure 1). They make up approximately 71% of all tropical glaciers (Vuille et al. 2008b) and the Cordillera Blanca is the most extensively glaciated mountain range in Peru, containing nearly a quarter of all tropical glaciers (Vuille et al. 2008b; Kaser, Georges 1999; Thompson et al. 1995). The mountain range stretches a distance of approximately 180 km and is 30 km wide. It includes more than 200 mountains higher than 5000 m, of which 27 are higher than 6000 m, such as Huascaran Sur (6768 m), the highest summit in Peru and one of the highest mountain ranges in South America. The shape and setting of the Cordillera Blanca make it a pronounced barrier to the easterly dominated atmospheric currents and it separates the dry Pacific side from the humid Amazon side. In addition, it forms the continental watershed draining into Rio Marañon and the Atlantic to the east and into Rio Santa and the Pacific to the west.
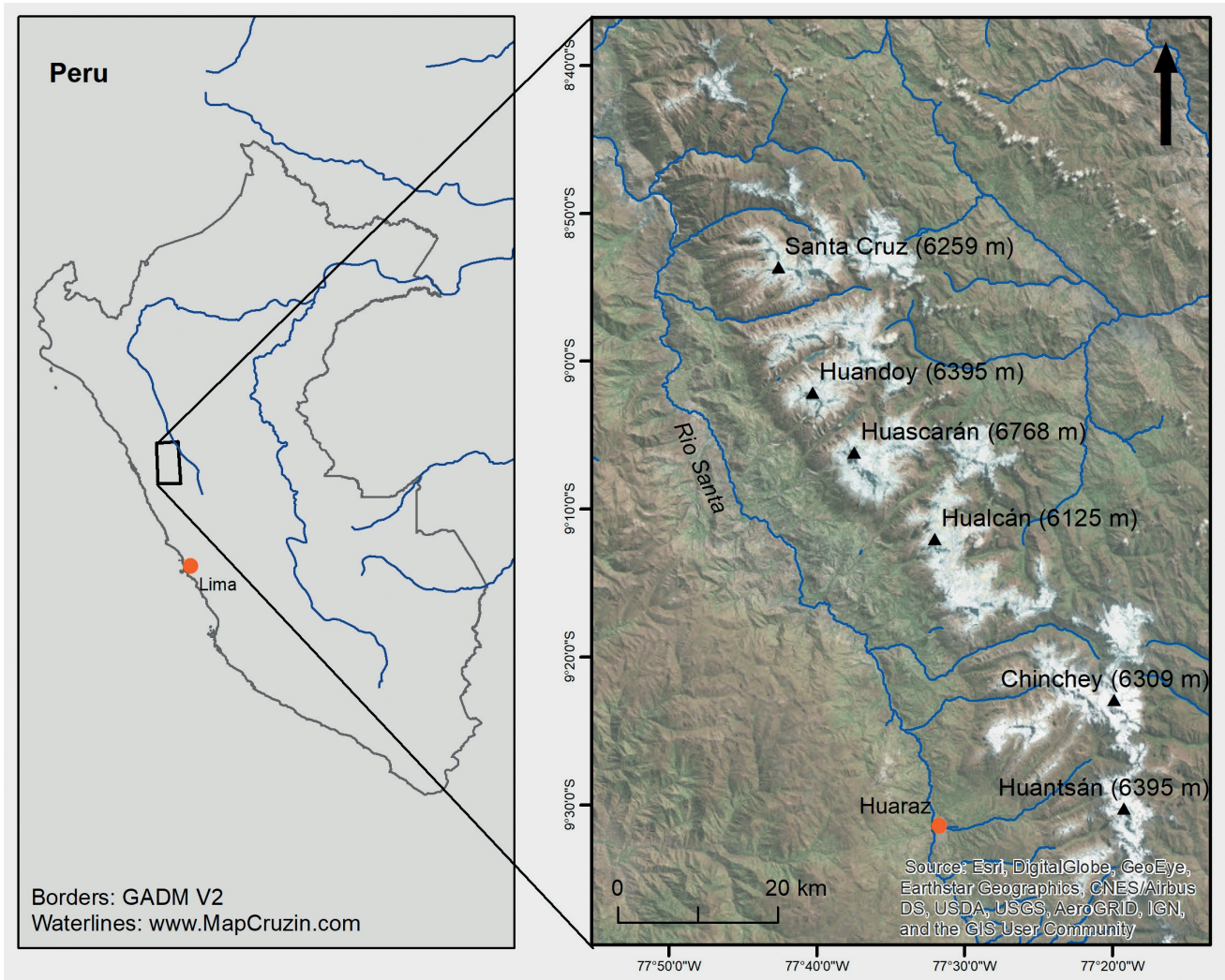
Fig. 1 Study area and localization of the main glaciers of the Cordillera Blanca.

2.1 Climate settings

The region is part of the outer tropics, which have a tropical character during the humid season and a subtropical character during the dry season (Kaser 2001). The humid season, which is influenced by the Intertropical Convergence Zone (ITCZ), occurs during the austral summer, October-April, during which 90% of the annual amount of precipitation is concentrated (Figure 2). Precipitation over the Cordillera Blanca mainly comes from the easterly advection of moist air masses from the Amazon basin and locally induced convective cells (Kaser, Georges 1999). The dry season influenced by trade winds occurs between May and September, during which time precipitation in the valley bottom is almost zero (Schauwecker et al. 2014). In contrast to the strong annual differences in precipitation, this area is characterized by small annual differences in temperature, but the diurnal amplitude has a wide variability (Vuille et al. 2008b).

Very little is known about the interannual climate variability related to large-scale atmospheric circulation in the Cordillera Blanca (Rangwala et al. 2015).

Nevertheless, there are some studies that document the significant impact of El Niño Southern Oscillation (ENSO) on temperature and precipitation in various regions of the tropical and subtropical Andes (Francou et al. 2003; Klimeš et al. 2009; Vilímek et al. 2000; Vuille 2003). Vuille at al. (2008b) used the glacier mass balance time series from the Cordillera Blanca region, which was reconstructed from the largest glaciers based on runoff measurements from stream gauges between 1953 and 1993. The results show a good overall correspondence between the two time series with negative mass balance anomalies during El Nino events and positive mass balance anomalies during La Nina events. This is similar to what was observed in Ecuador and Bolivia (Francou et al. 2003). However, this relationship was much stronger in the early part of the record and has weakened over the last 15–20 years. For example, during 1979/80 the mass balance was the most negative of the entire record despite weak El Nino conditions; 1982/83 had a near-normal mass balance despite the strongest El Nino of the entire record and
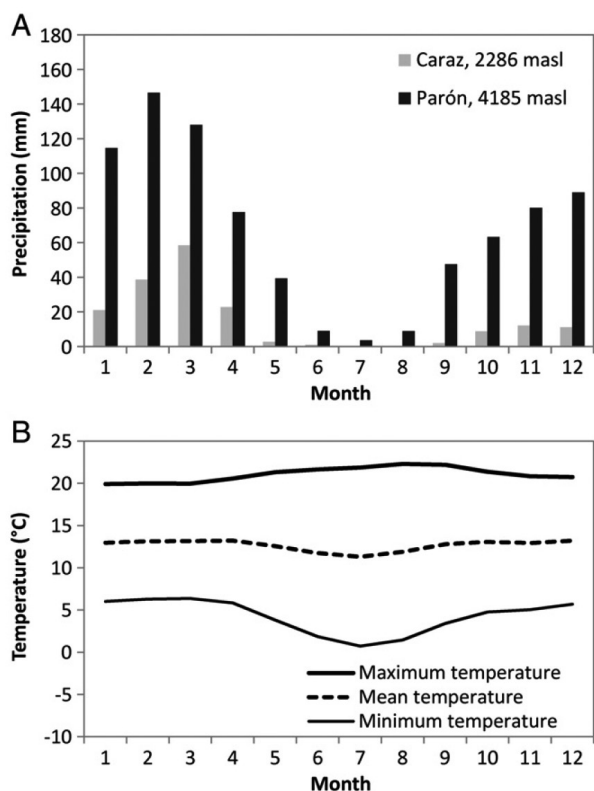
Fig. 2 Monthly precipitation and air temperature in the Cordillera Blanca. (a) Multiannual monthly mean precipitation registered at Caraz in the valley bottom (grey) and near Laguna Parón above 4000 m a.s.l. (black) between 1953 and 1995. (b) Multi-annual monthly mean of daily maximum, minimum and mean temperature for the Recuay station at 3444 m a.s.l. for the period 1980 to 2011. Source: Schauwecker et al. 2014

the turn of 1993/94 saw the strongest positive mass balance of the entire record despite neutral El Nino conditions.

2.2 Characteristics of glaciers

In order to understand how climate influences the glacier mass balance, it is important to know something about the basic characteristic glaciers in the Cordillera Blanca. The orientation of glaciers in the Cordillera Blanca is primary controlled by the structural trend of the Andes and thus reflects regional gradients in precipitation and solar radiation (Ames 1998). 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 (Francou et al. 2003; Wagnon et al. 1999).

Racoviteanu et al. (2008) presented the main characteristics of glaciers in the Cordillera Blanca, derived from SPOT imagery. In 2003, there were 485 glaciers covering an area of 569.6 km^2. The majority of glaciers are thin, strongly crevassed, slope type ice bodies without pronounced glacier tongues (Figure 3) and with an average slope of 32° (Ames 1998; Racoviteanu et al. 2008).

The few existing valley type glaciers form heavily debris covered glacier tongues (Kinzl 1942 in Georges 2004), covering an area of 14.9 km^2, which is 3% of the total glacier area (Racoviteanu et al. 2008). The average glacier orientation is 193° (southwest)

Fig. 3 Glaciers of the Santa Cruz valley (photo: A. Juřicová).

with 32% of the glaciers oriented towards the south and southwest. These results are similar to those discussed in Ames (1998), who reported an average glacier orientation of 187°. In the outer tropics of the Southern Hemisphere, where the Cordillera Blanca is located, these aspects are more shaded in the day during the wet season (Mark, Seltzer 2005). Therefore, the net energy balance is likely to be lower on southwest-facing aspects during the wet season, favoring precipitation as snow compared to rain, and reducing ablation as well. In this context, some glaciers can be more sensitive to solar radiation than to regional precipitation. Elevation of the glacier termini ranges from 4204 to 5369 m a.s.l. and glacier termini are 102 m higher on the western slope of the Cordillera Blanca (4914 m a.s.l.) than on the eastern slope (4812 m a.s.l.). The median elevation of the glaciers decreases from southwest to northeast, a trend represented by a tilted surface oriented towards the northeast. This southeast-northwest trend in glacier termini and median elevation reflects the orographic effect of the Cordillera Blanca, and is consistent with the regional gradient noted in previous studies (e.g. Kaser, Georges 1997). On the eastern side, increased precipitation due to orographic uplift from the Amazon basin favors the extension of glacier termini to lower elevations and induces a lower equilibrium line altitude (ELA) (Alatorre, Beguería 2009; Mark, Seltzer 2005; Kaser, Georges 1997). The Cordillera Blanca may be sensitive to small changes in climate because of the large number of small glaciers. There are glaciers with a mean size of 1.07 km^2 and the smallest glacier are only 0.006 km^2. The results show that small glaciers are much more common than large glaciers. On average, glaciers on the eastern side are slightly larger than those on the western side (Racoviteanu et al. 2008).

2.3 Climate trends

Several studies focusing on the climate trends in the tropical Andes have been published and a few of them focus especially on the Cordillera Blanca. We have chosen to refer to all of the tropical Andes because we analyzed longer time series and also because we wanted to underline the newest publications about the Cordillera Blanca.

2.4 Temperature trend

Vuille and Bradley (2000) were the first to investigate temperature trends in the tropical Andes. However, they did not specifically analyze temperatures in the region of the Cordillera Blanca. The data consisted of monthly means from 268 stations between 1°N and 23°S, ranging from 0 to 5000 m a.s.l for the period 1939–1998.

Table 1 shows the annual mean temperature trend from the 1939–1998 average over the last 60 years. There is a significant positive overall trend of 0.11 °C/decade between 1939 and 1998. Indeed,

the warming trend almost doubled over the period 1959–1998 (0.20 °C/decade) and more than tripled between 1974 and 1998 (0.34 °C/decade) compared to the entire 60 years period. There is also a pronounced pattern of reduced warming with increasing elevation on the western side. This vertical structure of the temperature trend is different from what is observed in Tibet or in the European Alps, where the warming is more pronounced at higher elevations (Vuille, Bradley 2000). In fact, there is growing evidence that the rate of warming is amplified with elevation, so that high-mountain environments experience more rapid changes in temperature than environments at lower elevations (Pepin et al. 2015). Elevation-Dependent Warming (EDW) can accelerate the rate of change in mountain ecosystems, cryospheric systems, hydrological regimes and biodiversity (Rangecroft et al. 2013). There are many important mechanisms that contribute towards EDW: snow albedo and surface-based feedbacks; water vapor changes and latent heat release; surface water vapor and radiative flux changes; surface heat loss and temperature change; and aerosols (Qin et al. 2009).

For the Cordillera Blanca region, Schauwecker et al. (2014) analyzed temperature change by calculating 30-year running mean changes for maximum, minimum and mean air temperature between 1960 and 2012. For the trend analyzes in this work, the area was separated into three regions: the Coastal region, the Cordillera region below 4000 m a.s.l. and the Cordillera region above 4000 m a.s.l. The Coastal region is defined for elevations up to 400 m. The following three reference stations were used: Recuay (3444 m a.s.l.) for the Cordillera region below 4000 m a.s.l., Artesoncocha (4838 m a.s.l.) for the Cordillera region above 4000 m a.s.l. and Buena Vista (216 m a.s.l.) for the Coastal region. For regions

Tab. 1 Temperature trends (°C/decade) for different time periods and elevation zones. The trends are based on Ordinary least squares (OLS) regressions. The trends shown in bold are significant at a 95% confidence interval (modified after Vuille, Bradley 2000).

	East	Andes	West
0–1000 m	0.00	–	0.39
500–1500 m	0.12	–	0.34
1000–2000 m	0.16	–	0.29
1500–2500 m	0.15	–	0.27
2000–3000 m	–	0.21	–
2500–3500 m	–	0.19	–
3000–4000 m	–	0.19	–
3500–4500 m	–	0.19	–
4000–5000 m	–	0.16	–
1939–1998	–	0.11	–
1959–1998	–	0.20	–
1974–1998	–	0.34	–

above 4000 m a.s.l., the results show that the temperature did not change between 2002 and 2012. For the Cordillera region (below 4000 m a.s.l.) the results show that there is reduced warming in the last 30 years compared to earlier decades (Figure 4). Between 1969 and 1998 the mean annual air temperature increased by 0.31 °C/decade and between 1983 and 2012 it increased by 0.13 °C/decade. The trends computed for a 30-year period before 1999 are also consistent with the results of Mark and Seltzer (2005). They showed a slightly reduced warming for 29 stations in the period 1962–1999 compared to the earlier period of 1951–1999. However, compared to the previous paper, they used stations ranging in elevation from 20 to 4600 m a.s.l. for the entire area.

The results also show that between 1983 and 2012 the minimum temperature increased by almost 0.29 °C/decade, while the maximum temperature decreased by approximately 0.04 °C/decade (insignificantly). The greater increase in the minimum
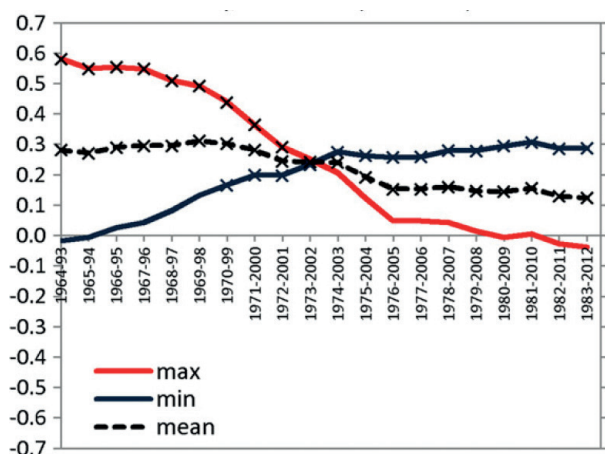

Fig. 4 Running 30-year air temperature trends between 1964 and 2012 for the Recuay reference station for the annual maximum, mean and minimum air temperature. Black crosses indicate significant 30-year trends at the 5% level (according to the Mann–Kendall test) based on annual data.
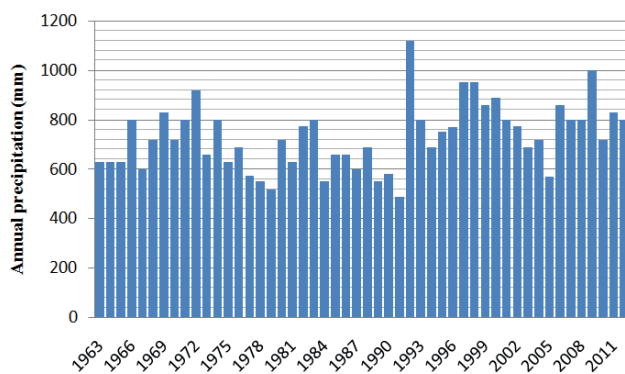Source: modified by Schauwecker et al. 2014

Fig. 5 Annual precipitation for the reconstructed Recuay final reference station at 3444 m a.s.l.
Source: modified after Schauwecker et al. 2014

temperature was during dry periods. While this trend is observed in the Cordillera Blanca, cooling was observed over the last 30 years at coastal stations in the Ancash region, which is similar to the results from the west coast of Chile and southern Peru (Falvey, Garreaud 2009).

2.5 Precipitation trends

According to Schauwecker et al. (Schauwecker et al. 2014) the mean annual precipitation increased between 1983 and 2012. The increase at the Recuay reference station (3444 m a.s.l.) was approximately 60 mm/decade (Figure 5). Between the 1980s and 1990s, the increase in annual precipitation observed at several stations was more than 200 mm, with the largest annual precipitation being observed in 1993. The shift in precipitation was observed for wet seasons, expect for dry seasons where precipitation was decreasing. For the dry season, the period between 1993 and 2002, which includes the wet year 1993, was the driest of all the observation periods.

An increase in precipitation was observed by Vuille et al. (2003) in northern Peru between 5°S and 11°S (1950 to 1994). However, no clear pattern emerges for general precipitation changes in the tropical Andes (e.g. Vuille et al. 2003; Rabatel et al. 2013). A weak tendency toward increased precipitation was observed in northern Peru between 5°S and 11°S by Vuille et al. (2003). However, there is no clear pattern for general precipitation changes in the tropical Andes (e.g. Francou et al. 2003; Rabatel et al. 2013).

2.6 Other characteristics (humidity, convective cloud cover)

Changes in humidity are very relevant in the context of glacier fluctuations because of the significant impact humidity has on the partitioning of the available energy into melt and sublimation. Unfortunately, in the Andes, no long-term and continuous in-situ measurements exist to document such changes. However, new data sets of tropospheric water vapor have become available thanks to improved remote sensing techniques. Vuille et al. (2003) found a significant increase in relative humidity in the Andes between 1950 and 1995 of up to 2.5%/decade. The major positive trend was in northern Ecuador and southern Colombia, while in southern Peru, western Bolivia and northernmost Chile the increase was more moderate (0.5–1.0%/decade). Given the significant increase in air temperature and the rising relative humidity levels, it follows that specific humidity has increased significantly throughout the Andes as well.

There are some datasets available in order to assess changes in cloud cover over the past few decades. One of them is the International Satellite Cloud Climatology Project (ISCCP). Unfortunately, it is not suitable for linear trend analysis due to a lack of long-term measurements. Another useful data set is based

on measurements of the outgoing long-wave radiation (OLR) that has been constantly monitored by a number of polar orbiting satellites since 1974. The largest changes took place during the austral summer, when OLR significantly decreased over the tropical Andes. This observed increase in convective activity and cloud cover in the inner tropics is consistent with earlier studies through the Andes (Vuille et al. 2003). In the outer tropics (south of ~15°S) the trend is reversed, featuring an increase in OLR. This pattern is more difficult to interpret because OLR in the outer tropics is a good proxy for convective activity and cloud cover during the rainy season. However, OLR has indeed significantly increased in the outer tropics during the rainy season as well, suggesting that cloud cover is trending downward. This overall pattern is consistent with the changes in precipitation.

Fig. 6 Progressive glacier recession, Nevado Ranrapalca, 6162 m a.s.l. (photo: V. Vilímek).

3. Glaciers

3.1 Modern glacier fluctuations

The word "modern" in the title of the chapter refers to the period from the LIA, when the glaciers of the tropical Andes (including Cordillera Blanca) had their last general maximum extent (e.g. Kaser 1999). Since this period, the glaciers have been continuously retreating. Progressive glacier recession was continuing throughout the 20th century and was interrupted by several periods of advancement. In the outer tropics, the LIA period is dated up to the 17th century, with dates varying slightly from one mountain range to another. Solomina et al. (2007) estimated, according to relative age of moraines, two main peaks of glacier advances during the LIA period. The first of them occurred between 1590 and 1720, a period which corresponds to the wettest phase in the tropical Andes in the last millennium as revealed by ice core data (Thompson et al. 1986). Younger and less extensive advance occurred between 1780 and 1880. It is clear that fluctuations of glaciers occurred before the LIA, but measurement is difficult due to a lack of available information (Kaser 1999). A comprehensive description of current knowledge about glacier fluctuation is given by Kaser and Osmaston (2002) and is summarized in Georges (2004).

A general glacier retreat in the Cordillera Blanca was observed by Sievers (1914 in Kaser 1999) during his journey through Peru and Ecuador in 1909. Before him, Broggi (1943 in Kaser 1999) quotes information from Raimondi, according to which the retreat started in 1862. This indicates that the retreat of glaciers started from the highest level of the LIA. Up to the 1920s the glaciers were melting but there eis no information about the intermediate advances. After then, the 1920 advance reached almost the former LIA extent. Much of the glacier shrinkage and tongue retreat of the 20th century may have occurred between 1930 and 1950, when a significant rise in

ELA was observed and quantitatively derived from the aerial pictures (Kaser 1999). Since the beginning of the 1970s, the changes of the lengths of the tongues have been measured on single glaciers (Hastenrath and Ames, 1995). During the first half of the 1970s, the glaciers were in equilibrium or even advancing slightly (Kaser 1999).

The ice recession was not uniformly distributed in a temporal view but was strong in the 1930s and 1940s and intermediate from the mid-1970s until the end of the century. At the end of the 20th century, there is another phase of advancement. After the 1997/1998 El Nino, predominant La Nina conditions led to low temperatures and weak dry seasons. Therefore, some glaciers slightly advanced (1999–2002 field observation of the Tropical Glaciology Group, Innsbruck) (Georges 2004).

Glacier recession accelerated in the Peruvian Andes over the three last decades of the 20th century (Burns, Nolin 2014; Francou, Vincent 2007; Raup et al. 2007). Thus, from 1970 to 1997 the glacier coverage in Peru declined by > 20% (Bury et al. 2011; Fraser 2012), and this has been associated with higher lake levels and a marked increase in landslides, flash floods and mud flows, often with dramatic consequences.

Some glaciers have been well documented. On the Huascaran-Chopicalqui glacier, the glacier extent decreased from 71 km^2 in 1920 to 58 km^2 in 1970 and ELA rose by 95 m (Kaser et al. 1996). On the Artesonraju glacier, a tongue retreat of 1140 m was observed between 1932 and 1987. The terminus of the nearby Broggi glacier retreated 1079 m between 1932 and 1994, despite a slight advance around 1977 (Ames 1998). The Pucaranra and Uruashraju glaciers lost 690 m and 675 m in length, respectively between 1936 and 1994. A similar analysis of the Yanamarey glacier showed that its tongue lost 350 m between 1948 and 1988 (Hastenrath, Ames 1995) and 552 m between 1932 and 1994 (Ames 1998).

Glacier retreat was accompanied by significant loss of ice volume. From 1948 to 1982, the volume loss of the Yanamarey glacier was estimated to be 22×10^6 m^3, with an additional loss of 7×10^6 m^3 between 1982 and 1988 (Hastenrath, Ames 1995). In the Queshque massif of the southern Cordillera Blanca, Mark and Seltzer (2005) estimated a glacier volume loss of 57×10^6 m^3 between 1962 and 1999.

According to Hidrandina (1988), 711 glaciers were inventoried in 1970, with a total area of 721 km^2 (excluding the Nevados Rosco and Pelagatos). Most of the glaciers, 91% of the total, are classified as mountain glaciers; they are generally short and have extremely steep slopes. The rest are classified as valley glaciers, except for one ice cap. Georges (2004) present a comprehensive overview of the entire Cordillera Blanca based on SPOT satellite images and digitized maps, and suggests an overall decline in glacierized area from ~850–900 km^2 during the LIA to 800–850 km^2 in 1930, 660–680 km^2 in 1970, and 620 km^2 in 1990. A similar study detected a glacier area of 643 km^2 in 1987, and 600 km^2 in 1991 (Silverio, Jaquet 2005).

One of the latest papers about glacier extent throughout the Cordillera Blanca (Burns, Nolin 2014) describes more detailed changes in the glacier area between 1987 and 2010. The Cordillera Blanca was divided into several watersheds, where the change in glacier extent was measured. The estimated entire glacier area is 643.5 km^2 ($\pm$30 m) for 1987 and 482.4 km^2 ($\pm$30 m) for 2010. More detailed analysis shows that for the Llanganuco watershed, the total change in glacier area from 1987 to 2010 was 6.5 km^2, or 19.5% relative to 1987. For the Rio Santa watershed up to the La Balsa station, the total change in glacier area from 1987 to 2010 was 91.5 km^2, or 23.2% relative to 1987. Over the entire Cordillera Blanca, glaciers lost 161 km^2, or 25% of their area relative to 1987. It was also examined how the glacier area changed for watersheds as a function of initial median glacier elevation and aspect. In general, the sub-watersheds with the most glacier-covered area appear to be most representative of the changes observed for the Callejón de Huaylas and the entire Cordillera Blanca. Watersheds with the lowest median glacier elevation lost the most glacier area from 1987 to 2010. The Querocochaya watershed is an exceptional example of the total percental glacier area loss because it is a watershed with a lower maximum elevation and lower median glacier elevation. Glacier aspect also appears to be important. The eastern slope of the Cordillera Blanca (147 km^2 in 2010) lost 27% of 1987 glacier area, while the western slope (336 km^2 in 2010) lost 25% of 1987 glacier area. It would expect glaciers on the eastern slopes to lose a greater percentage of their area because they are lower on average (Kaser, Georges 1997).

In general, from the LIA maximum extent to the beginning of the 20th century, glaciers in the Cordillera Blanca retreated a distance of approximately 1000 m (+/−30% of their length), comparable the rate observed during the 20th century (Vuille et al. 2008b).

3.2 Equilibrium line altitude changes

The observed changes in glacier dimensions also helped estimate the changes in the equilibrium line altitude (ELA). In Peru, reconstructions of variations in length were based on a GPS survey of the moraines, combined with analyses of aerial and terrestrial photographs, historical documents, and old topographic maps. Historical documents from before the late 19th century that report fluctuations in tropical glaciers are rare (Wagner 1870 in Jomelli et al. 2009). From the maximum 17th century extent to the late 19th century, the ELA increased by approximately 108 ± 30 m. A significant shift in the ELA was observed between 1930 and 1950 in the Santa

Tab. 2 Glacier area estimates for each of the sub-watersheds as well as the entire Cordillera Blanca. The last column shows area change between 1987 and 2010 (modified after Burns and Nolin 2014).

Watershed	Area (km²)				Area change (km²)
	1987	1996	2004	2010	
Paron	18.7	17.9	17.3	16.1	−2.5
Llanganuco	33.1	31.8	31.1	26.7	−6.5
Marcara (Chancos)	66.9	59.5	60.5	51.4	−15.5
Cedros	20.6	18.3	18.0	14.0	−6.6
Colcas	41.4	37.7	37.6	32.6	−8.5
Quilcay	44.1	39.8	39.2	32.7	−11.5
Pachacoto	15.8	13.7	12.4	9.9	−5.9
Olleros	20.6	16.8	16.0	12.2	−8.4
Santa (La Balsa)	394.4	362.9	352.2	302.9	−58.7
Quitrasca	27.9	24.6	23.2	18.8	−9.1
Querococha	3.5	2.1	2.1	0.9	−2.5
Cordillera Blanca	**643.5**	**584.0**	**569.4**	**482.4**	**−161**

Cruz-Alpamayo – Pucahirca massif (almost 70 m on some slopes). During the 20th century, the shift in the ELA was more than 150 m in some places (Jomelli et al. 2009). Similar results are reported in Schauwecker et al. (2014). The freezing line altitude increased by about 160 m between 1960 and 1980 during the wet season. This large increase before 1980 probably caused a significant shift in the ELA.

4. Discussion

Long-term measurements suggest that warming in the tropical Andes could likely explain the retreat observed over the last few decades. Unfortunately, despite the slowdown of the temperature rise and increase in precipitation, glacier retreat has continued at a high rate over the last few decades for several reasons. The rising temperature may be the most likely candidate for the observed glacier retreat over the last few decades; however, glaciers may also be influenced by a negative mass balance due to negative trends in precipitation and/or enhanced absorption of solar radiation due to a decrease in cloudiness.

4.1 Factors controlling changes in the mass balance of tropical glacier

Changes in air temperature may affect tropical glacier mass balance in two ways: 1. by increasing ablation rates and 2. by shifting the position of the 0 °C isotherm and thus determining whether precipitation falls as rain or snow (Racoviteanu et al. 2008; Kaser, Osmaston 2002). Larger increases in air temperature at lower elevations result in a large upward shift in the 0 °C isotherm, causing more precipitation to fall as rain than as snow at higher elevations. This diminishes the accumulation area and reduces the local albedo, which in turn increases the net solar radiation and promotes enhanced melting rates at lower elevations.

Furthermore, precipitation is also important for the accumulation process. Notable accumulation occurs only during the wet season in this region, when an increase in precipitation leads to an increase in solid precipitation in the accumulation area and, thus, a more positive annual mass balance. During the dry season, there is little accumulation and ablation, because of the dry air, much of the available energy is consumed by sublimation and, therefore, little remains for melting (Kaser 2001; Wagnon et al. 1999).The precipitation increase observed during the wet season leads to an increase in solid precipitation in the accumulation area, and thus a more positive annual mass balance. Unfortunately, the shift in precipitation can probably not balance the negative mass balance caused by a strong increase in air temperature and the related changes in the freezing line and the snowline (Schauwecker et al. 2014).

In addition, increasing air temperatures during precipitation events lead to a rise in the snowline.

The ablation process of a glacier is controlled by the energy balance on the glacier surface. Glacier melt in the tropics depends to a large degree on surface albedo and the sensitivity of glaciers to changes in albedo is high (Rabatel et al. 2013). The surface albedo of glaciers is largely influenced by the state of precipitation, and the transition of snow to rain is closely related to air temperature. The freezing line altitude increased during precipitation events between 1960 and 1980. Consequently, net radiation absorption was higher when the glacier is without snow cover and more energy was available for melt (Schauwecker et al. 2014). In addition, higher air temperatures may lead to an increased sensible heat flux, which also results in increased ablation. However, this is generally small compared to the energy supplied by shortwave and long-wave radiation (Wagnon et al. 1999). Schauwecker et al. (2014) mentioned that the role of humidity and cloud cover is an unknown and reliable station data are still missing. Cloud feedbacks have long been identified as the largest internal source of uncertainty in climate change predictions, even without considering the interaction between clouds and aerosols (Cess et al. 1990; Houghton et al. 2001). Recent comparisons of feedbacks produced by climate models under climate change show that the current generation of models still exhibits a large spread in cloud feedbacks, which is larger than for other feedbacks (Bony et al. 2006). However, the decreased daily temperature range may indicate higher humidity and cloud cover in the last few decades. An increase in cloud cover would result in lowered incoming shortwave and increased incoming long-wave radiation (Sicart al. 2010). Specific humidity, on the other hand, is crucial in the process of latent heat fluxes, since it determines the fraction of sublimation. In the Cordillera Blanca, sublimation consumes 60 to 90% of the total available energy during the dry season (Sicart 2005; Winkler et al. 2009). Since sublimation of ice needs 8.5 times more energy than melt, a decrease in the fraction of sublimation may lead to drastically increased ablation rates.
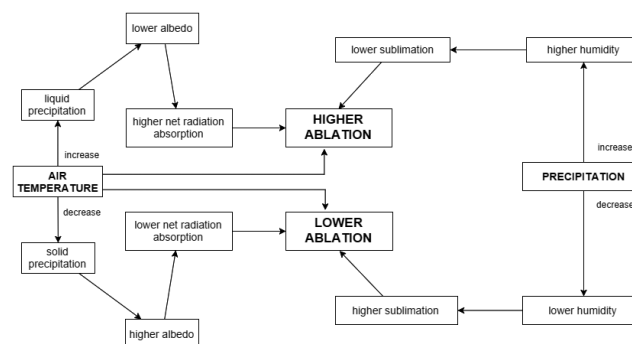

Fig. 7 Main factors controlling changes in the mass balance of tropical glacier.

4.2 Relationship with a large-scale climate

Due to the increase in the glacier terminus retreat observed throughout the Cordillera Blanca, it is clear that the glaciers do not have to be in balance with the regional climate. As detailed energy and mass balance studies on glaciers in the outer (Bolivia) or in inner tropics (Ecuador) show, the temperature does not play such a dominant role (Francou et al. 2003; Wagnon et al. 1999) even though it is still significantly correlated with mass balance on interannual timescales at both locations. Francou et al. (2003) argued that this relationship between temperature and mass balance is caused by the role of temperature as an integrating factor of climate, being strongly related to other more important variables, such as humidity, cloud cover or precipitation. The result shows that throughout the tropical Andes, wet years tend to be cold, while warm years are predominantly dry. This situation also seems to be the case in the Cordillera Blanca (Vuille et al. 2008a). The results suggest that precipitation between October and April is a more important variable for explaining mass balance variability in the Cordillera Blanca region, and that the climate signal embedded in the glacier mass balance record is not just local, but at least of regional significance. This analysis, however, fails to explain whether the relationship between precipitation and mass balance is primarily due to the direct impact of precipitation (for accumulation) or rather indirectly due to changes in the albedo and the receipt of net-shortwave radiation on the glacier surface.

The characteristics of a tropical climate and its influence on glacier fluctuation are difficult to describe. The Andes and the Cordillera Blanca are a difficult area for analyzing meteorological values because of the arid desert on the west side and the large humid Amazon basin (Vuille et al. 2003). In addition, meteorological stations are not distributed uniformly through the region. More stations are located in the lower part than in the highest part of the mountain. For this reason, the data must be reanalyzed and homogenized (Venema et al. 2013). There are three widely used reanalysis products, one of which is from the National Center for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR). According to Schauwecker et al. (2014), this data may have limitations for analyzing regional trends in air temperature and need careful evaluation. In addition, all of the tropical Andes, including the Cordillera Blanca, are characterized by large regional differences and climate warming may be spatially heterogeneous and temporally discontinuous. This is why we decided to include data about all of the tropical region as well.

5. Conclusion

Here we presented a summary of all of the newest information about the main changes in meteorological values and distribution of glaciers in the Cordillera Blanca.

Temperature and precipitation changes do not completely explain the strong glacier retreat during the past few decades. As we describe above, the relationship between glacier behavior and climate change is very complicated. It also involves glacier characteristics, local morphological conditions (slope, aspect, etc.), local and regional climate and large-scale-climate settings. The general driver of these changes is probably a change in the regional climate due to similar mass balance changes throughout the Cordillera Blanca. However, local conditions are also important, because every glacier has a slightly different response to changes. This is why, for example, the elevation of glaciers is lower on the southwest side than on the northeast side. Glaciers at lower elevations are more sensitive to climate change. The glaciers in the Cordillera Blanca may also be particularly sensitive to small changes in climate, because most of the glaciers are very small, thin, have extremely steep slopes, and are at a low elevation. As Schauwecker et al. (2014) suggests, the recent glacier retreat observed during the last 30 years may still occur in response to the strong temperature rise before 1980 and the related strongly unbalanced glacier states. On glaciated mountains and in watersheds, climate change – acting in combination with other environmental and societal factors – has already caused notable, and in some cases catastrophic, consequences as glaciers retreat (Carey 2010; Clague, Evans 2000; Haeberli et al. 1989; Kääb et al. 2005; Raup et al. 2007; Richardson, Reynolds 2000). In fact, the Cordillera Blanca has produced some of the world's most deadly glacier disasters, and urban areas, including Carhuaz on the banks of the Santa River and its tributaries, have been the most exposed to GLOFs and glacier avalanches.

Information about the 'climate sensitivity' of glaciers is useful for predicting the terminus response, meltwater runoff and glacier contribution to sea-level rise under future climate change (Oerlemans et al. 1998), and for using paleoglacial extents to reconstruct past climate change (Anderson et al. 2010; Anderson, Mackintosh 2006). Several broader questions also emerge for an understanding of the related permafrost degradation. This is especially important in arid areas like the Andes, where fresh water stored in permafrost can be important for local water management in small catchments (Colombo et al. 2016).

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