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Climate change and tropical Andean glaciers: Past, present and future

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ABSTRACT

Observations on glacier extent from Ecuador, Peru and Bolivia give a detailed and unequivocal account of rapid shrinkage of tropical Andean glaciers since the Little Ice Age (LIA). This retreat however, was not continuous but interrupted by several periods of stagnant or even advancing glaciers, most recently around the end of the 20th century. New data from mass balance networks established on over a dozen glaciers allows comparison of the glacier behavior in the inner and outer tropics. It appears that glacier variations are quite coherent throughout the region, despite different sensitivities to climatic forcing such as temperature, precipitation, humidity, etc. In parallel with the glacier retreat, climate in the tropical Andes has changed significantly over the past 50–60 years. Temperature in the Andes has increased by approximately 0.1 °C/decade, with only two of the last 20 years being below the 1961–90 average. Precipitation has slightly increased in the second half of the 20th century in the inner tropics and decreased in the outer tropics. The general pattern of moistening in the inner tropics and drying in the subtropical Andes is dynamically consistent with observed changes in the large-scale circulation, suggesting a strengthening of the tropical atmospheric circulation. Model projections of future climate change in the tropical Andes indicate a continued warming of the tropical troposphere throughout the 21st century, with a temperature increase that is enhanced at higher elevations. By the end of the 21st century, following the SRES A2 emission scenario, the tropical Andes may experience a massive warming on the order of 4.5–5 °C. Predicted changes in precipitation include an increase in precipitation during the wet season and a decrease during the dry season, which would effectively enhance the seasonal hydrological cycle in the tropical Andes.

These observed and predicted changes in climate affect the tropical glacier energy balance through its sensitivity to changes in atmospheric humidity (which governs sublimation), precipitation (whose variability induces a positive feedback on albedo) and cloudiness (which controls the incoming long-wave radiation). In the inner tropics air temperature also significantly influences the energy balance, albeit not through the sensible heat flux, but indirectly through fluctuations in the rain–snow line and hence changes in albedo and net radiation receipts.

Given the projected changes in climate, based on different IPCC scenarios for 2050 and 2080, simulations with a tropical glacier–climate model indicate that glaciers will continue to retreat. Many smaller, low-lying glaciers are already completely out of equilibrium with current climate and will disappear within a few decades. But even in catchments where glaciers do not completely disappear, the change in streamflow seasonality, due to the reduction of the glacial buffer during the dry season, will significantly affect the water availability downstream. In the short-term, as glaciers retreat and lose mass, they add to a temporary increase in runoff to which downstream users will quickly adapt, thereby raising serious sustainability concerns.

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1. Introduction

In the arid and semiarid regions of the tropics and subtropics more than 80% of the freshwater supply originates in mountain regions, affecting populations downstream (Messerli, 2001). Much of this water is initially stored as ice in mountain glaciers and then gradually released over time. More than 99% of all tropical glaciers are located in the Andes (Kaser, 1999) and Andean countries, such as Bolivia or Peru, rely to a great extent on freshwater from glaciated basins during the dry season. Mountain glaciers, such as those found in the tropical Andes, therefore act as a critical buffer against highly seasonal precipitation and provide water for domestic, agricultural or industrial use at times when rainfall is low or even absent. At the same time these glaciers are particularly sensitive to climate change because they are constantly close to melting conditions. They are arguably the most visible indicator of climate change, due to their fast response time, their sensitivity to climate variations and the clear visibility of their reaction (glacier growth or shrinkage) to the public.

This looming threat of changes in water supply associated with tropical glacier retreat has received little attention so far, mostly because the climate change community is very much focused on observed and projected large climatic changes at high northern latitudes. However, these global projections rely on models, which due to their coarse resolution, are inadequate to resolve the steep topography of long and narrow mountain chains, such as the Andes. As a consequence, climate change at high tropical locales is not well simulated in these models. Indeed, when considering the rate of warming in the free troposphere (e.g. Bradley et al., 2004, 2006) rather than at the surface, it becomes evident that warming in the tropical Andes is likely to be of similar magnitude as in the Arctic, and with consequences that may be felt much sooner and which will affect a much larger population.

A number of studies have investigated various aspects of this problem, including case studies of glacier mass and energy balance (e.g. Wagnon et al., 1999a,b, 2001; Francou et al., 2003, 2004; Kaser et al., 2003), observational studies on past and future climate change (i.e. Vuille and Bradley, 2000; Vuille et al., 2003a; Bradley et al., 2004, 2006), or consequences of glacier retreat for water resources downstream (i.e. Mark and Seltzer, 2003; Mark et al., 2005; Mark and McKenzie, 2007; Juen et al., 2007). A comprehensive analysis however, linking glaciological, climatological and hydrological aspects of this problem, has been missing. The goal of this study is thus to combine all these factors in an integrated, multidisciplinary synthesis in order to assess the current state of knowledge, but also to document where our understanding is still inadequate. Ideally such a synthesis should also provide a scientific basis for stakeholders and decision makers when discussing adaptation measures to future hydrologic changes in the region.

Section 2 documents observed historical changes in glaciation in the tropical Andes since the end of the Little Ice Age. A review of observed changes in climate during the 20th century in Section 3 helps to put the observed cryospheric changes into a climatic context. A detailed description of how glaciers interact with and respond to changes in climate by adjusting their mass balance, and how the energy received at the glacier surface is consumed by melting and sublimation processes is given in Section 4. A brief discussion of 21st century climate change projections is followed by an assessment of the potential ramifications of the observed and projected future glacier retreat for glacier discharge and downstream water supplies (Section 5). We end with some concluding remarks and some recommendations as to how the scientific network in the Andes should be expanded and how collaboration between disciplines could be improved (Section 6).

2. Glacier variations since the Little Ice Age (LIA)

In the following section we focus primarily on glacier fluctuations since the end of the Little Ice Age. A thorough review of glacier retreat and advance throughout the past millennium can be found in Jomelli et al. (in press). We focus exclusively on glaciers in Ecuador, Peru and Bolivia (Fig. 1). Venezuela still has a few glacier remnants totaling less than 2 km^2, but they have lost more than 95% of their glacier-covered area since the mid-19th century (Schubert, 1998). In Colombia six different mountain ranges still have glacier coverage, but glaciology remains a very young science in this country where detailed observations and mass balance studies are just starting, so results from these programs are not yet available (Ceballos et al., 2006). Finally Chile also has a few glaciers in its northernmost corner along the border with Bolivia in the Cordillera Occidental that can be considered tropical in the broadest sense.

2.1. Ecuador

The glaciers in Ecuador are located on two mountain chains, the Cordillera Occidental and the Cordillera Oriental. They are found at lower elevation in the Cordillera Oriental because it is exposed to the moisture supply from the Amazon basin. Various historical sources indicate a rather extensive glaciation from the 1500s to the first part of the 1800s, with a maximum glacial extent around AD 1730 (Jomelli et al., in press). The following ice recession was interrupted by several smaller advances around 1800, 1850 and 1870 but otherwise continued to the present time (Hastenrath, 1981; Jomelli et al., in press). Between the 18th century and today the estimated rise of the Equilibrium Line Altitude (ELA) is approximately 250 m (Jomelli et al., 2008b). More detailed information is available for the last few decades, thanks primarily to the tropical glacier monitoring program, spearheaded by the French Institut de Recherche pour le Développement, IRD. Detailed measurements on Antizana 15 glacier (Fig. 1), including monitoring of glacier length changes and glacier mass balance have been conducted since 1994. This ice cap, located only 40 km east of Quito is of special interest given the use of its glacial runoff for the capital's water supply (Francou et al., 2004). Aerial photogrammetry, starting in 1956 has been used to put the on-site monitoring, which started in 1995, in a longer-term perspective. Results show a rapid retreat between 1995 and 1999, which was 7–8 times faster than during the previous period, 1956–1993 (Francou et al., 2000). Between 1999 and 2001 glaciers advanced, due to a cool and wet phase associated with persistent La Niña conditions in the tropical Pacific (Francou et al., 2004). Since 2001 glaciers have again been rapidly retreating (Fig. 2). Results from a study on nearby Cotopaxi volcano (Fig. 1) confirm the observations on Antizana. Cotopaxi glaciers were almost stagnant between 1956 and 1976 and then lost approximately 30% of their surface area between 1976 and 1997 (Jordan et al., 2005). The calculated total mass (thickness) loss on selected snouts of Cotopaxi between 1976 and 1997 equals 78 m, or 3–4 m w.e. yr^{-1}, very similar to the values obtained on Antizana.

2.2. Peru

The Peruvian Andes contain the largest fraction of all tropical glaciers (~70%), and glaciers in Peru are among the best studied in the tropical Andes. In the Cordillera Blanca (Fig. 1), the world's most extensively glacier-covered tropical mountain range, and in other parts of Peru, glaciers reached their maximum extent between 1630 and 1680 (Jomelli et al., in press). An earlier glacial advance occurred around AD 1330±29 (Solomina et al., 2007; Jomelli et al., 2008a, in press), but was overlapped by the LIA maximum glacial advance around AD 1630±27 on most glaciers. During the 17th–18th centuries at least three glacial advances were recorded synchronously on several glaciers (AD 1670±24, 1730±21 and 1760±19). Significant glacier recession started in the middle of the 19th century (Ames, 1998; Kaser, 1999 and references therein; Kaser and Osmaston, 2002; Solomina et al., 2007). From the LIA maximum extent to the beginning of the 20th century, glaciers in the Cordillera Blanca retreated a distance of about 1000 m (~30% of their length), comparable

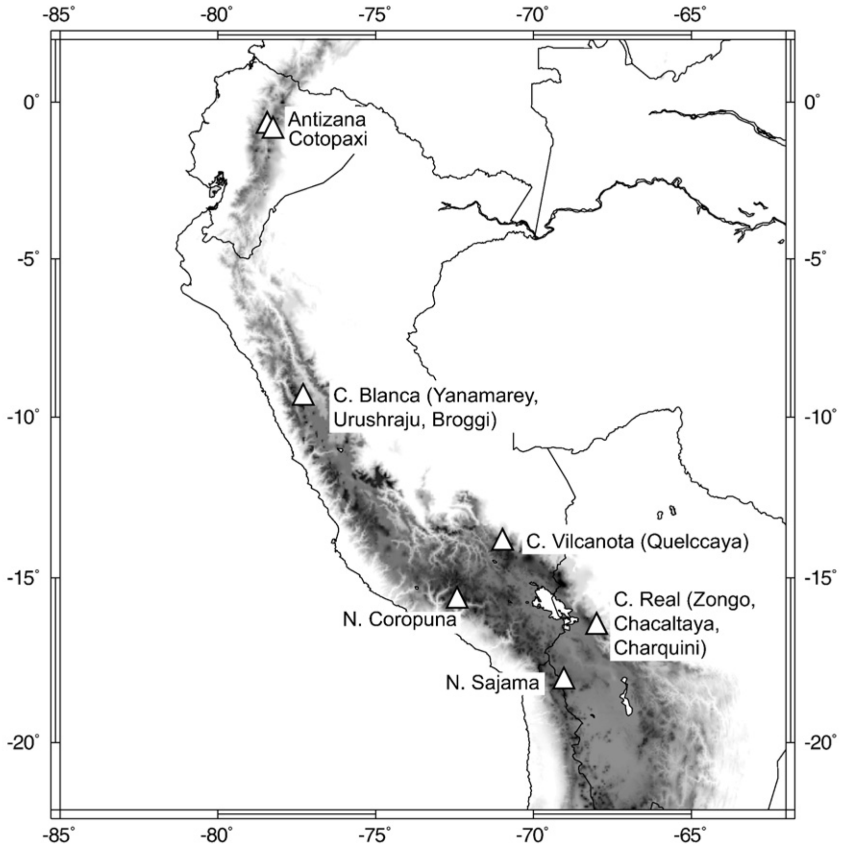

Fig. 1. Area map with location of key sites discussed in the text.

to the rate observed during the 20th century. Estimates of paleo-ELAs show an increase in altitude of about 100 m from the LIA maximum glacial extent at the beginning of the 17th century to the beginning of the 20th century (Jomelli et al., in press). Much of the glacier shrinkage and tongue retreat of the 20th century in the Cordillera Blanca may have occurred in the time between 1930 and 1950, when a significant rise of the ELA, which separates the accumulation from the ablation zone, was observed. Yet there is evidence for at least three phases of advance, one in the mid-1920s (Ames, 1998; Kaser, 1999), one in the late 1970s (Kaser and Georges, 1997), and most recently at the end of the 20th century (Georges, 2004). These advances however, were short-lived and did not stop the general trend of retreat. On Huascaran–Chopicalqui for example, the glacier extent decreased from 71 km^2 in 1920 to 58 km^2 in 1970 and the ELA rose by ~95 m (Kaser et al., 1996a). On glacier Artesonraju a tongue retreat of 1140 m was observed between 1932 and 1987 (Ames, 1998), while the glacier surface area decreased by 20% between 1962 and 2003 (Raup et al., 2006). Nearby glacier Broggi's terminus retreated 1079 m between 1932 and 1994, despite a slight advance around 1977 (Ames, 1998). Glacier Pucaranra and glacier Uruashraju lost 690 m and 675 m respectively in length between 1936 and 1994 (Ames, 1998). A similar analysis on glacier Yanamarey showed that its tongue retreated by 350 m between 1948 and 1988 (Hastenrath and Ames, 1995a) and 552 m between 1932 and 1994 (Ames, 1998). At the end of the 20th century glacier retreat on Yanamarey continued unabated with an estimated 20 m yr^{-1} (average 1977–2003), four times the rate observed between 1948 and 1977 (Mark et al., 2005).

Fig. 2 contains a summary of the observed terminus retreat from five Cordillera Blanca glaciers: Yanamarey, Broggi, Pastoruri, Uruashraju and Gajap. In general glacier retreat was rapid in the late 1980s and early 1990s and then slowed down in the late 1990s and early 2000s, consistent with observations in Ecuador. Over the last few years the retreat seems to again have gained momentum.

Glacier retreat was accompanied by significant loss of ice volume. From 1948 to 1982 volume loss on Yanamarey was estimated at 22×10^6 m^3, with an additional loss of 7×10^6 m^3 between 1982 and 1988 (Hastenrath and Ames, 1995a). Mark and Seltzer (2005a) estimated a glacier volume loss of 57×10^6 m^3 between 1962 and 1999 in the Queshque massif of the southern Cordillera Blanca. This translates into an area-averaged glacier ice thinning of 5–22 m and an estimated ELA rise of 25–125 m, depending on the aspect of the glacier.

A comprehensive overview of the entire Cordillera Blanca based on SPOT satellite images and digitized maps, 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. The ice coverage at the end of the 20th century was estimated to be slightly less than 600 km^2 (Georges, 2004). A similar study on the basis of Landsat TM data detected 643 km^2 of glacierized area in 1987, and 600 km^2 in 1991 (Silverio and Jaquet, 2005). These differences are mostly due to different methodologies and definitions as to what should be included as 'glacier' (e.g. peripheral snow fields, snow covered ground above the glacier accumulation zone, stagnant debris-covered ice, etc.).

While glaciers in the Cordillera Blanca have received the most attention, some case studies on glacier retreat in other regions of Peru exist, such as in the Cordillera Vilcanota (Seimon et al., 2007), on Qori Kalis, an outlet glacier from the Quelccaya ice cap (Brecher and Thompson, 1993; Thompson et al., 2006), or on Coropuna (Fig. 1) in the western Cordillera Ampato (Racoviteanu et al., 2007). These regions have all experienced similar glacier retreat as the Cordillera Blanca, with the glaciated area on Coropuna decreasing from 82.6 km^2 in 1962 to 60.8 km^2 in 2000 (Racoviteanu et al., 2007) and with a retreat rate of the terminus of Qori Kalis that was 10 times faster (~60 m yr^{-1}) between 1991 and 2005 than in the initial measuring period, 1963–1978 (Thompson et al., 2006). It is noteworthy to mention that the tongues of both Artesonraju and Qori Kalis have retreated from a flat basin into a steep rock face and, in the

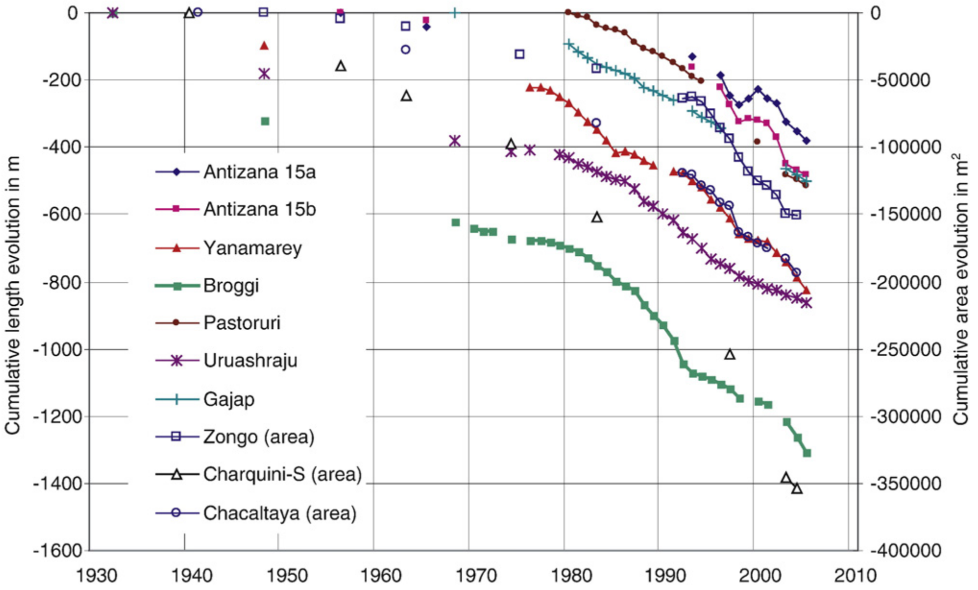

Fig. 2. Change in length and surface area of 10 tropical Andean glaciers from Ecuador (Antizana 15a and 15b), Peru (Yanamarey, Broggi, Pastoruri, Uruashraju, Gajap) and Bolivia (Zongo, Charquini, Chacaltaya) between 1930 and 2005.

case of Artesonraju, beyond; changing retreat rates therefore have to be interpreted very carefully.

2.3. Bolivia

Glaciers in Bolivia can be found in two main mountain ranges, the Cordillera Occidental along the western border with Chile and the Cordilleras Apolobamba, Real, Tres Cruces and Nevado Santa Vera Cruz in the east. Glaciers in the Cordillera Occidental are limited to Nevado Sajama and its neighboring volcanoes on the border with Chile (Fig. 1). They consist of small summit ice caps on extinct volcanoes, which due to the dry conditions have the highest minimum elevation on earth, with an ELA several hundred meters above the 0 °C isotherm (Messerli et al., 1993; Arnaud et al., 2001). Most glaciers, however, are located in the eastern Cordilleras and consist of ice caps, valley and mountain glaciers. Because of the limited precipitation, no glaciers exist today in southern Bolivia (Messerli et al., 1993).

Most information on past glacier extent stems from the Cordillera Real (Fig. 1), where IRD started a detailed monitoring and research program on several glaciers in the early 1990s. The maximum neoglacial advance occurred during the second half of the 17th century (Rabatel et al., 2005, 2006; Jomelli et al., in press). As in the Cordillera Blanca two smaller glacial advances occurred in the Cordillera Real in the 1730s and 1760s respectively (Rabatel et al., 2008; Jomelli et al., in press). Afterwards glaciers started to retreat with a major recession occurring in the late 19th century and an even more rapid retreat after 1940 and especially since the 1980s (Jomelli et al., in press). Glaciers on Charquini for example have by now lost between 65 and 78% (depending on aspect) of their LIA size and the ELA rose by approximately 160 m from ~4900 m during the LIA maximum extent to ~5060 m in 1997 (Rabatel et al., 2006). Recession rates have increased by a factor of 4 over the last decades and Charquini glaciers experienced an average mass deficit of 1.36 m w.e. yr^{-1} between 1983 and 1997. However, the apparently large retreat observed on Charquini is put into perspective, when considering that these glaciers are all very small. In absolute terms all glaciers on Charquini have lost less than 1 km^2 of their surface area since the LIA (Rabatel et al., 2006). On larger glaciers, such as nearby Zongo, the relative mass loss is therefore much lower. Nonetheless Zongo glacier is equally in imbalance as demonstrated by a reconstruction of glacier discharge since the early 1970s, which shows that the glacier is losing more mass than is replenished by precipitation (Ribstein et al., 1995). Probably most notable however, is the rapid ice wastage on Chacaltaya glacier, which lost 62% of its mass between 1940 (0.22 km^2) and 1983 and whose remaining size in 1998 was only 0.01 km^2 or 7% of the extent in 1940 (Francou et al., 2000). On average the glacier experienced 3–5 times higher ablation rates in the 1990s than in previous decades, with an average loss of 1.4 m w.e. yr^{-1}. The glacier also lost 40% of its thickness in only 6 years from 1992 to 1998, as well as two thirds of its total volume (Ramirez et al., 2001). The small elevation range covered by the glacier (270 m in 1991) essentially meant that it had lost its accumulation zone, as the ELA had moved above the uppermost reaches of the catchment. In the early 1990s the glacier still functioned as a small ski resort, while today the glacier has essentially disappeared and disintegrated into a few small stagnant ice fields (Coudrain et al., 2005). Chacaltaya is a very small and low-lying glacier, and therefore particularly vulnerable to climate change. The retreat of such small glaciers is accelerated once they reach a critical size, below which 'edge effects' become important. At the edge of tropical glaciers air temperature above surrounding rocks can exceed 20 °C at daytime (Francou et al., 2003), and hence advection of warm air above the glacier can become very important. Nonetheless Chacaltaya must be considered representative of many glaciers in the region, since more than 80% of all glaciers in the Cordillera Real are less than 0.5 km^2 in size (Francou et al., 2000). Indeed mass balance on Chacaltaya and the much larger Zongo glacier feature very similar interannual variability and longer-term trends (Figs. 2 and 3), although data from Zongo are from the ablation zone only. The negative trend on Chacaltaya was interrupted briefly in 1992/93, 1996/97 and 2000/01. On the other hand the glacier lost a third of its entire volume (6 m w.e.) in an exceptional 18 month period between 1997 and 1999 (Fig. 3).

In summary, observations on length and area variations from glaciers in Ecuador, Peru and Bolivia give a detailed and unequivocal account of rapid retreat of tropical Andean glaciers since the LIA. While the climatic forcing behind this retreat may have varied over time and may not necessarily be the same everywhere, evidence for a coherent regional pattern is beginning to emerge (Fig. 2). Mass balance records from Bolivia and Ecuador similarly show a very coherent picture, featuring a generally negative mass balance, that appears to be driven by the same background forcing throughout the region

(Fig. 3). Superimposed on the generally negative trend (Fig. 3a) are occasional periods of equilibrated or even positive mass balance (Fig. 3b), that tend to slow down or even temporarily reverse the negative cumulative trend (Fig. 3a) These periods often coincide with prolonged La Niña events, such as between 1999 and 2001, which are associated with cool and wet conditions in both the Andes of Bolivia (Vuille et al., 2000a) and Ecuador (Vuille et al., 2000b).

3. Observed 20th century climate change

To accurately attribute glacier retreat to a particular climate forcing requires detailed knowledge and understanding of the climatic changes that have taken place in the 20th century. In this section we will review regional scale, observed 20th century climate change by focusing on variables which are relevant for the glacier energy balance.

3.1. Temperature

Fig. 4 shows an analysis of near-surface temperature trends based on a compilation of 279 station records between the 1°N and 23°S. These results are based on an update of previous studies by Vuille and Bradley (2000) and Vuille et al. (2003a) through 2006. Individual station records have been assembled into a single time series by using the first difference method and by first gridding the data to avoid any regional bias (Vuille and Bradley, 2000). The results show that near-surface air temperature has significantly increased over the last ~70 years. An ordinary least squares regression analysis indicates a warming of 0.10 °C/decade and an overall temperature increase of 0.68 °C since 1939. Of the last 20 years only 2 (1996 and 1999) were below the long-term (1961–90) average. This rate of warming is similar to previous reports of 0.10–0.11 °C/decade between 1939 and 1998 (Vuille and Bradley, 2000) and 0.15 °C/decade between 1950 and 1994 (Vuille et al., 2003a).

On a more regional scale a number of studies provide additional evidence for significant warming over the last decades of the 20th century. In central Peru (9–11°S), Mark (2002) and Mark and Seltzer (2005a), based on 29 low and high-elevation stations, found a temperature increase of 0.35–0.39 °C/decade between 1951 and 1999. Vuille et al. (2000a,b) based on a principal component analysis of station data found a significant warming trend since the mid-1970s in southern Bolivia and northernmost Chile. Toumi et al. (1999) reported significant warming (0.20 °C/decade between 1954 and 1987) at La Quiaca, a high-elevation (3462 m) station at the border between Bolivia and Argentina by utilizing station pressure change as an indicator of warming. Quintana-Gomez (1997), based on daily temperature records from seven stations in the central Andes of Bolivia, showed that both minimum and maximum temperatures have increased between 1918 and 1990, but the trend for the minimum temperatures was much larger, thereby effectively reducing the daily temperature range (DTR). Similar results were obtained in a study from Ecuador, based on 15 stations between 1961 and 1990, revealing again an increase in both minimum and maximum temperatures, but a decrease of the DTR (Quintana-Gomez, 2000). Vincent et al. (2005) later confirmed these results with a limited data set from South America, showing that the DTR decreased from Ecuador to Chile. They also reported that the coldest nights are getting warmer and that the percentage of extremely cold (warm) nights is decreasing (increasing), thereby confirming the strong nighttime warming. Analyses of changes in freezing level height (FLH) over the American Cordillera and the Andes, based on NCEP–NCAR reanalysis data show an increase of 73 m between 1948 and 2000 and of 53 m between 1958 and 2000, a period for which the data is considered more reliable (Diaz et al., 2003). A simple regression analysis with the Niño-3 index shows that a 1 °C warming of tropical Pacific SST equals about 76 m rise of the FLH. Diaz et al. (2003) concluded that the increase in tropical Pacific SST accounts for about half of the observed rise in FLH, consistent with similar results obtained by Vuille et al. (2003a). Further evidence for recent warming comes from the Quelccaya ice cap, where shallow ice cores reveal that the seasonal δ^{18}O signal is no longer being preserved. This indicates that melting is taking place on the summit and that meltwater percolates through the snowpack, thereby destroying the seasonal δ^{18}O signal (Thompson et al., 1993; Thompson, 2000). This hypothesis is consistent with recent temperature recordings by an automated weather station at the summit, indicating that temperatures reach above freezing during several months every year (Hardy, pers. comm., 2007). Thompson et al. (2003, 2006) also reported a significant enrichment of the δ^{18}O in their cores during the 20th century that they have interpreted as a sign of rising temperatures. The correct interpretation of this signal, however, is controversial and most evidence suggests that it may not be directly related to a temperature increase (Bradley et al., 2003; Hardy et al., 2003; Vuille et al., 2003b,c; Hoffmann et al., 2003; Hastenrath et al., 2004; Vuille and Werner, 2005; Vimeux et al., 2005, in press).

3.2. Precipitation

Changes in precipitation are much less notable than the changes in temperature. There is however, also a lack of long and high-quality precipitation records, which would allow for a detailed assessment of long-term trends. Vuille et al. (2003a) used 42 station records between

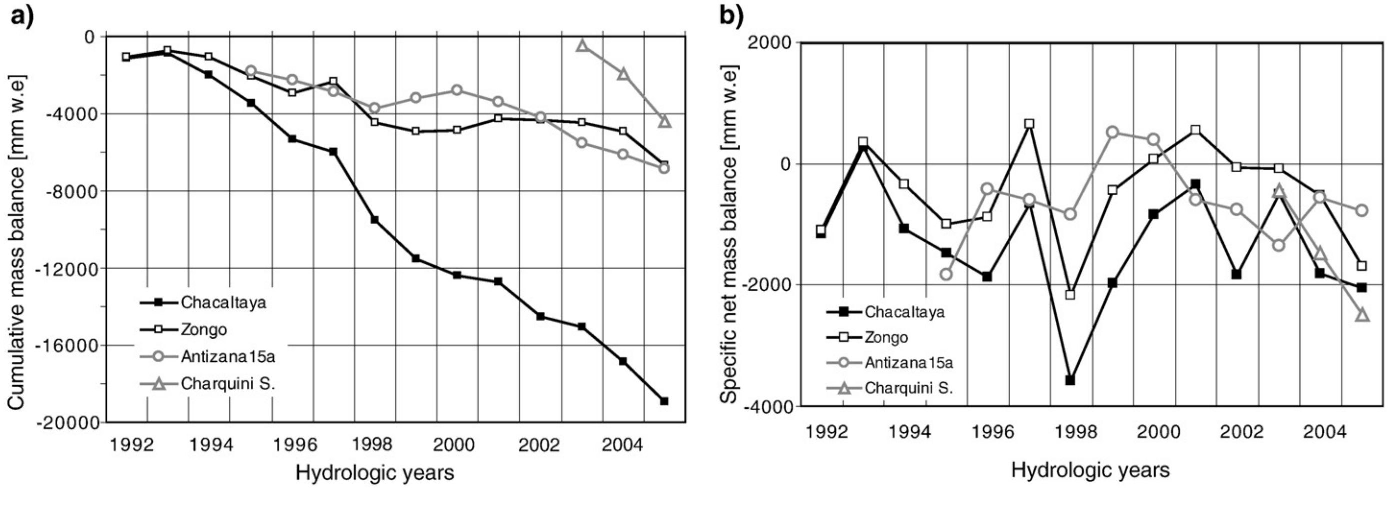

Fig. 3. Comparison of a) cumulative and b) annual mass balance on glaciers in Bolivia and Ecuador. Note that the hydrological year is September–August in Bolivia and January–December in Ecuador.

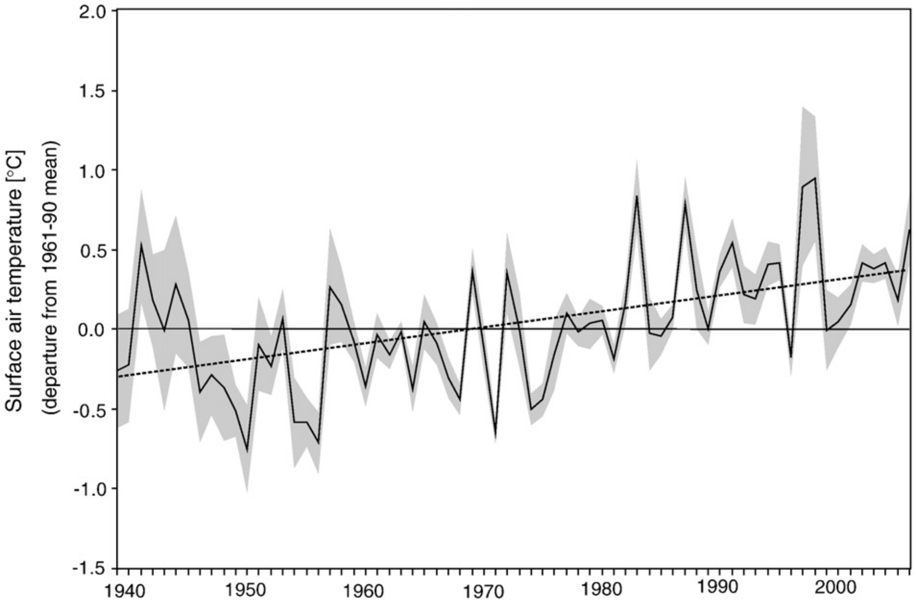

Fig. 4. Annual temperature deviation from 1961–90 average in the tropical Andes (1°N–23°S) between 1939 and 2006 based on a compilation of 279 station records. Gray shading indicates ±2 standards errors of the mean. Black line shows long-term warming trend (0.10 °C/decade) based on ordinary least square regression.

1950 and 1994 to analyze trends in precipitation in the Andes of Ecuador, Peru, Bolivia, and northernmost Chile and Argentina. Besides determining the statistical significance, Vuille et al. (2003a) also analyzed the trends for spatial coherence and elevation dependence. There is a tendency for increased precipitation north of ~11°S, in Ecuador, northern and central Peru both on annual time scales and at the height of the austral summer precipitation season (DJF). In southern Peru and along the Peru/Bolivia border on the other hand, most stations indicate a precipitation decrease. Even though this appears to be a quite coherent regional signal, individual station trends are mostly insignificant. Of the 42 stations analyzed only 5 (2) show a significant increase (decrease) in the annual precipitation amount and there is no apparent dependence of the trend on elevation. These results were later confirmed by Haylock et al. (2006), who also found a change toward wetter conditions in Ecuador and northern Peru, and a decrease in southern Peru, albeit based on far fewer stations. A few studies have looked at precipitation trends on a regional scale and found notable precipitation increases over time. It is interesting that all these reports come from the eastern slopes of the Andes, or even the lowlands to the east, such as the reported increase along the eastern slopes of the Andes in Ecuador during the MAM rainy season (Vuille et al., 2000b), or along the eastern slopes in NW-Argentina (Villalba et al., 1998).

3.3. Humidity

Changes in humidity are very relevant in the context of glacier variations because of the significant impact humidity has on the partitioning of the available energy into melt and sublimation (see Section 4.3.). However, in the Andes, no long-term and continuous in-situ records exist to document such changes. New data sets of tropospheric water vapor have become available thanks to improved remote sensing techniques, but they have their own calibration issues and the records in general are still too short to meaningfully distinguish between low-frequency variability and actual trends. NCEP–NCAR and ERA-40 reanalysis data equally have large biases, particularly in their moisture fields and over the tropics, making them ill suited for any kind of trend analysis (Trenberth and Guillemot, 1998; Trenberth et al., 2001). In their assessment of near-surface humidity changes in the Andes, Vuille et al. (2003a) therefore relied on CRU05 data, which is based on station observations, spatially interpolated on a regular 0.5°×0.5° grid (New et al., 2000). They found a significant increase in relative humidity between 1950 and 1995 of up to 2.5%/decade. The most prominent 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), To the east of the Andes the trends were much lower or even negative. Given the significant increase in temperature and the rising relative humidity levels, it follows that vapor pressure (or specific humidity) has increased significantly throughout the Andes as well. However, since the CRU05 data are partially interpolated from synthetic data (New et al., 2000), these trends need to be interpreted with caution (Vuille et al., 2008).

3.4. Convective cloud cover (OLR)

The most comprehensive data set available to assess changes in cloud cover over the past decades is the International Satellite Cloud Climatology Project (ISCCP), which has been used in the past to study cloud cover variations in the central Andes (Vuille and Keimig, 2004). Unfortunately it is not very well suited for linear trend analysis because of its short duration (start in July 1983) and the lack of an independent confirmation of the long-term calibration (e.g., Rossow and Schiffer, 1999). Another commonly used data set is based on measurements of the outgoing long-wave radiation (OLR) emitted by the earth's surface and the overlying atmosphere and constantly monitored by a number of polar orbiting satellites since 1974. OLR is sensitive to the amount and height of clouds over a given region and time and has been applied in a number of studies to investigate tropical convection and convective cloud cover over tropical South America (e.g. Chu et al., 1994; Aceituno and Montecinos, 1997; Liebmann et al., 1998; Chen et al., 2001; Vuille et al., 2003a). In the presence of deep convective clouds, the satellite sensor measures radiation emitted from the top of the clouds, which are high in the atmosphere and thus cold, leading to low OLR values. In the case of clear sky conditions on the other hand, high OLR values reflect radiation emitted from the earth's surface and the lower atmosphere. In the absence of convective clouds, OLR is thus strongly influenced by other processes, such as changes in surface temperature, low-level cloud cover or water vapor content. Fig. 5 depicts OLR trends between 1974 and 2005. The largest changes have taken place during austral summer, DJF, when OLR has significantly decreased over the tropical Andes and to the east over the Amazon basin (Fig. 5b). This observed increase in convective activity and cloud cover in the inner tropics is consistent with earlier studies over the Andes and the Amazon basin reaching

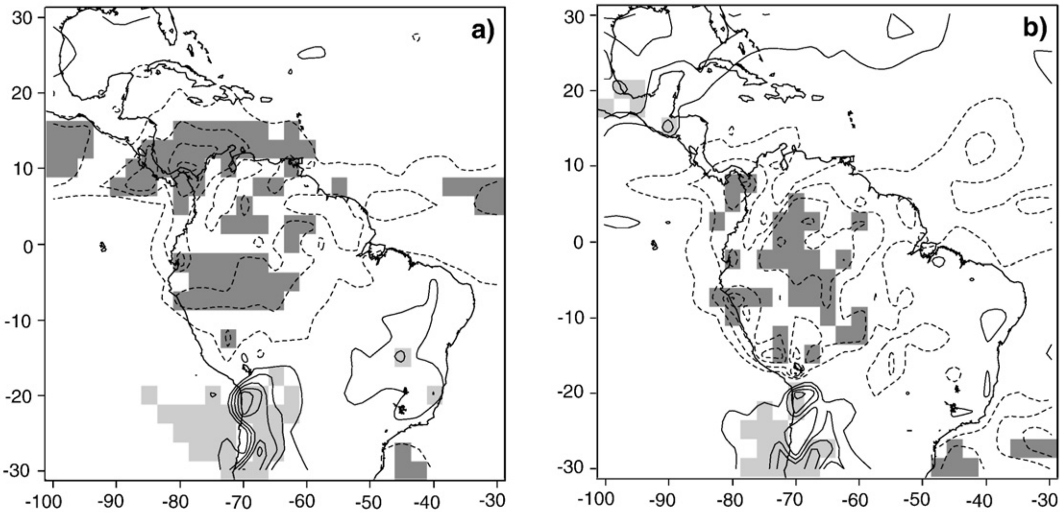

Fig. 5. Trends in OLR (in W m^{-2} yr^{-1}; 1974–2005) for a) annual mean and b) DJF. Contour interval is 0.1 W m^{-2} yr^{-1}; 0-contour is omitted and negative contours are dashed. Regions where increase (decrease) in OLR is significant at the 95% level are shaded in light (dark) gray.

similar conclusions (e.g., Chu et al., 1994; Chen et al., 2001; Vuille et al., 2003a). In the outer tropics (south of ~15°S) the trend is reversed, featuring an increase in OLR (Fig. 5a). This pattern however is more difficult to interpret because OLR in the outer tropics is only a good proxy for convective activity and cloud cover during the rainy season (DJF). However, OLR has indeed significantly increased in the outer tropics during DJF as well, suggesting that cloud cover is indeed trending downward (Fig. 5b). This overall pattern is consistent with the changes in precipitation reported in the previous section, with changes in vertical motion associated with the Hadley circulation (see next section) and with results by Wielicki et al. (2002) and Chen et al. (2002), who reported intensified upward motion and cloudiness in equatorial-convective regions and drier and less cloudy conditions in subtropical subsidence regions in the 1990s. However, questions have been raised about the reality of the variations in these latter two reports (Trenberth, 2002).

3.5. Atmospheric circulation

Although the significance of the observed trends varies widely, the previous sections on precipitation and cloud cover seem to suggest that the inner tropics are getting wetter and cloudier while the outer tropics are becoming drier and less cloudy. This behavior could be explained through an intensification of the meridionally overturning tropical circulation (the regional Hadley circulation), with more vigorous vertical ascent, favorable for convective activity, in the tropics, balanced by enhanced subsidence and accordingly clear skies in the subtropics. A trend analysis of the vertical motion (Ω) and the meridional wind field (v) along a north–south transect at 65°W in South America does indeed support this notion (Fig. 6). The result shows that over the period analyzed (1950–1998), the regional Hadley circulation has indeed intensified, with more vigorous ascent in the tropics between ~10°S and 10°N and enhanced descending motion in the subtropics, in particular in upper- and mid-tropospheric levels between 10°S and 30°S. This pattern is robust both in the annual mean as well as in the seasonal analysis, although the trends are larger and more significant in the northern hemisphere. The upper and lower tropospheric divergent wind field were subjected to similar analyses and the trends are dynamically consistent with the above results (Fig. 7). Although the divergent wind field is only a fraction of the total wind field, it is more directly linked to monsoonal precipitation, gives a better representation of the anomalous large-scale overturning (Hadley and Walker) circulation and it allows for an easier depiction of the centers of large-scale convergence and divergence (Trenberth et al., 2000). As shown in Fig. 7a, the upper tropospheric circulation shows a clear trend towards enhanced divergence over tropical South America, while the lower level (850 hPa) features increased convergence (Fig. 7b). Both of these fields act to reinforce and sustain enhanced upward motion and convective activity in the tropics, consistent with the notion that there has indeed been a trend toward a strengthening of the tropical circulation. Chen et al. (2001) came to very similar conclusions, showing that the regional hydrological cycle over the Amazon basin has strengthened, and vapor flux convergence over the basin has increased. Chen et al. (2002) also report a strengthening of the Hadley circulation, based on satellite observations, which show that equatorial-convective regions have intensified in upward motion and moistened, while both equatorial and subtropical subsidence regions have become drier and less cloudy. It should be noted however, that this trend seen in atmospheric reanalysis is not observed in rawinsonde data nor is it reproduced in most General Circulation Models (Allan and Soden, 2007). Nonetheless the trends are dynamically consistent with observational data (both OLR and in-situ precipitation) and help to explain why the Andes in the inner tropics appear to have become wetter and the subtropical Andes are becoming drier. In-situ observational data, satellite information and reanalysis data all seem to indicate such a strengthening of the tropical atmospheric circulation.

Whether such a trend will continue in the 21st century, however, is not clear. Climate model simulations performed for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) suggest a weakening of the tropical circulation in response to increased greenhouse gas concentrations. Most of this relaxation in the tropical overturning circulation however, takes place in the zonally asymmetric (Walker) circulation, while the Hadley circulation seems less affected (Vecchi and Soden, 2007). The simulated weakening of the Walker circulation over the tropical Pacific domain is consistent with observations by Curtis and Hastenrath (1999) which showed that sea level pressure (SLP) increased in the western and decreased in the eastern tropical Pacific throughout the 20th century. Vecchi et al. (2006) attributed this change to increased anthropogenic greenhouse gas forcing. The observed SLP changes in the Pacific lead to a weakened zonal SLP gradient and hence to a shift of the mean conditions toward a more El Niño-like state. This is relevant in the context of our discussion of Andean glaciers because of the strong dependence of the glacier mass balance on tropical Pacific SSTs and ENSO in particular. Of course a change in the mean state is different from a change in El Niño intensity or frequency, and it is not clear what the exact ramifications of these studies for Andean glaciers are. Nonetheless future changes in

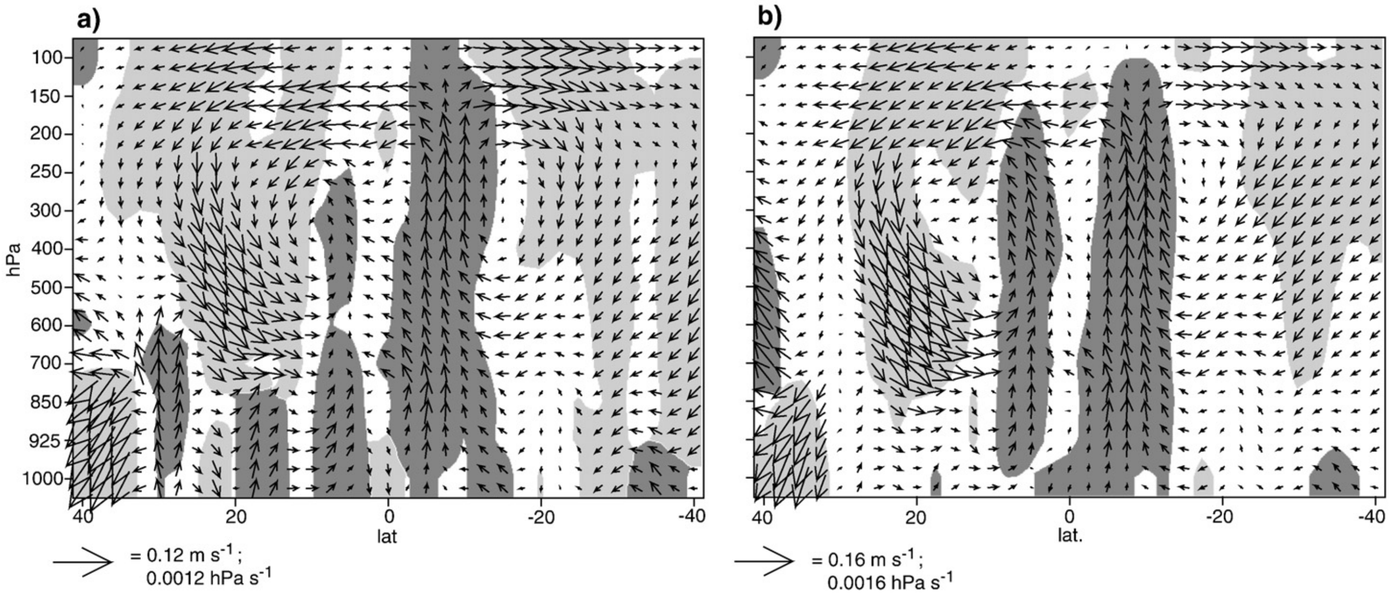

Fig. 6. Trend of vertical motion (Ω, in hPa s^{-1} yr^{-1}) and the meridional wind field (v, in m s^{-1} yr^{-1}) along a transect from 40°N to 40°S at 65°W between 1950 and 1998 for a) annual mean and b) DJF. Trends of enhanced ascending (descending) motion, significant at the 95% level, are shaded in dark (light) gray.

tropical Pacific climate need to be carefully observed, given the tight coupling between tropical Pacific SST and tropical Andean glacier mass balance, discussed in the next section.

4. Tropical glacier mass and energy balance

The principal processes that drive energy and mass fluxes toward and from the surface of a tropical glacier, and link a glacier with its surrounding climate, are exactly the same as on any mid- or high-latitude glacier. Yet the characteristics of tropical climate require a careful examination of each component of the energy and mass balance in terms of its efficiency on daily, seasonal and interannual time scales. Such an assessment is crucial for understanding the glaciers' sensitivity to changes in climate.

Because of the lack of a pronounced thermal seasonality (temperatures stay more or less constant throughout the year) but a clear differentiation between dry and wet seasons (one each in the outer tropics, almost constant precipitation near the equator), tropical glacier mass balance and its sensitivity to climate change are fundamentally different from mid- and high-latitude glaciers (see Kaser, 2001 and Kaser and Osmaston, 2002 for a detailed review). Unlike mid-latitude glaciers where accumulation and ablation are separated into a winter accumulation and a summer ablation season, tropical glacier ablation and accumulation can occur at the same time. Also, because temperature does not change much throughout the year, ablation occurs predominantly in the ablation zone below the ELA, and accumulation is restricted to regions above the snow-rain line that remains at more or less constant altitude throughout the year.

Apart from the pioneering work on energy balance by Hastenrath (1978) and early mass balance measurements carried out by Alcides Ames in the 1960s and 1970s (Kaser et al., 1990) (pre-1970 records were lost in the 1970 earthquake (Patzelt, 1983), detailed energy and mass balance studies in the tropical Andes only started in the late 1990s. These mass and energy balance studies are restricted to glaciers

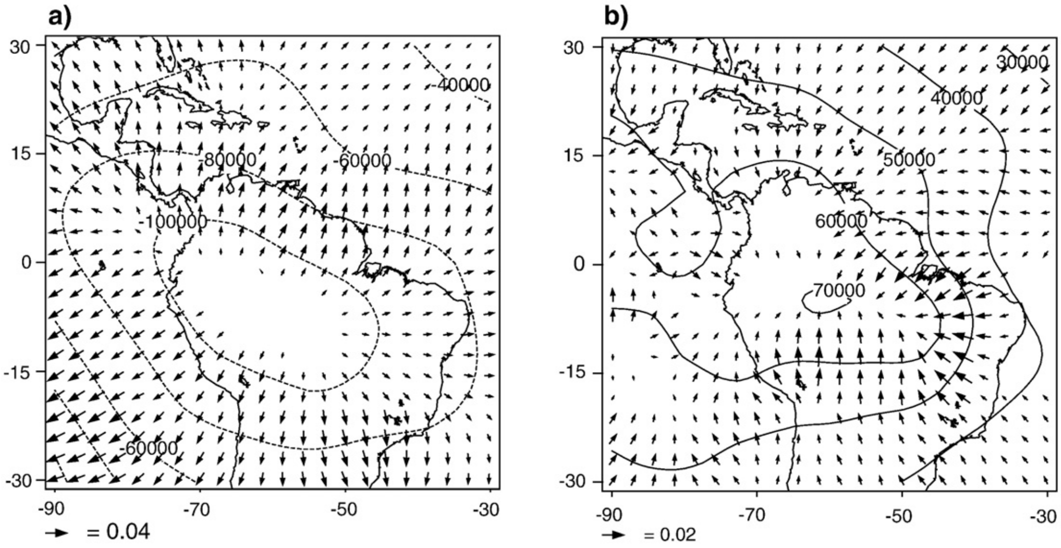

Fig. 7. Trend of velocity potential (χ, in m^2 s^{-1} yr^{-1}) and divergent wind field (u_{div}, v_{div}, in m s^{-1} yr^{-1}) between 1950 and 1998 for a) 250 hPa and b) 850 hPa level. Divergent wind vectors are only shown where the trend is significant at the 95% level.

that are easily accessible and safe to work on due to logistical reasons. In effect this means that they are usually rather small and relatively low-lying. This in turn may affect the results to some degree, as there are indications that small and low-lying glaciers have more negative mass balances and have experienced greater loss than colder glaciers, located in higher, inaccessible terrain (Francou et al., 2005). In addition, mass balance measurements are often limited to the ablation zone because of safety concerns, but also because the lack of a clear annual stratigraphy makes accumulation measurements very difficult (e.g. Kaser and Georges, 1999). Finally the limited sampling density (estimates for entire glaciers are often derived form a limited number of stakes) can lead to inaccurate or biased results, especially during extremely negative or positive years (Sicart et al., 2007). These limitations should be kept in mind during the following discussion.

4.1. Seasonality of mass balance and climate

The longest continuous mass balance measurements with stake networks are located on Zongo and Chacaltaya glaciers in Bolivia. On these glaciers, large year-to-year differences in mass balance occur during the wet season, October–April, while mass balance is always near equilibrium during the dry and cold months May–September (Fig. 8a). Accordingly, the annual mass balance largely reflects the variability in wet season accumulation and ablation. On Chacaltaya, for example, the three month DJF alone account for 78% of the total variance of the annual mass balance (Francou et al., 2003). In the Andes of Ecuador, on the other hand, mean ablation rates are nearly constant all year round (Fig. 8b), although the periods February–May and September show much larger variations from year to year. The large variability during those months can be explained by the dominant influence of ENSO on the glacier mass balance (Francou et al., 2004) and the large differences that occur in the seasonal cycle during the two opposite phases of ENSO (see Section 4.2.).

4.2. Interannual mass balance variations and their relationship with climate

On interannual time scales there is a clear inverse relationship between mass balance on Chacaltaya and temperature (Fig. 9a). Periods of negative (positive) mass balance values coincide with positive (negative) temperature anomalies. Temperature in this region, however, is strongly correlated with humidity, cloudiness and precipitation, especially on interannual timescales. Since temperature integrates all the fluxes, it appears to be significantly correlated with mass balance on longer timescales, but this apparent correlation does not reflect the real physical processes present at the glacier surface (Francou et al., 2003). ENSO plays an equally important role in dictating interannual mass balance variability, with El Niño years featuring a strongly negative mass balance and La Niña events producing a nearly balanced or even slightly positive mass balance on glaciers in Bolivia (Francou et al., 1995, 2000; Wagnon et al., 2001; Ramirez et al., 2001). These results do not come as a surprise since climate in the tropical and subtropical Andes is significantly influenced by ENSO on interannual timescales (Vuille, 1999; Vuille et al., 2000a,b; Garreaud and Aceituno, 2001; Garreaud et al., 2003; Vuille and Keimig, 2004), with La Niña years tending to be wet, while dry conditions usually prevail during El Niño years. In conjunction with dry conditions, the Andes also experience above average temperatures during El Niño events (Vuille and Bradley, 2000; Vuille et al., 2003a). On average, near-surface summer temperatures are 0.7–1.3 °C higher during El Niño as compared to La Niña (Vuille et al., 2000a). Tropical glaciers, such as Chacaltaya, thus do not only experience a deficit of summer precipitation and consequently reduced accumulation and a lowered albedo during El Niño events, but are also exposed to higher temperatures and an increase in incoming short-wave radiation due to reduced cloud cover (Wagnon et al., 2001; Francou et al., 2003). It follows that mass balance anomalies on Chacaltaya are largely governed by climatic conditions in the tropical Pacific domain (Francou et al., 2003). This is consistent with observations indicating an accelerated negative mass balance and glacier retreat in many tropical Andean locations after the mid-1970s, concurrent with the 1976/77 Pacific climate shift.

Results from Antizana similarly indicate a strong dependence on ENSO, with a mass balance that is negative all year round during El Niño periods but remains close to equilibrium during La Niña events (Francou et al., 2004). While the response to ENSO-related climate variability is very similar on Antizana to what is observed on glaciers in Bolivia, the seasonal dependence and the physical mechanisms linking ENSO with mass balance variations are very different (Favier et al., 2004a). Unlike in Bolivia, the impact of El Niño is primarily through increased air temperature, which favors rain over snowfall, but to a lesser degree also due to weak and sporadic snowfall, insufficient to maintain a high glacier albedo, low wind speeds, which are more favorable for melting than sublimation, and reduced cloud cover, which increases the incoming short-wave radiation. La Niña events on the other hand are characterized by colder temperatures, higher snowfall amounts, and to a lesser degree, more constant winds, factors which increase albedo and sublimation and therefore reduce melting at the glacier surface (Francou et al., 2004). Hence on interannual time scales mass balance is equally closely related to

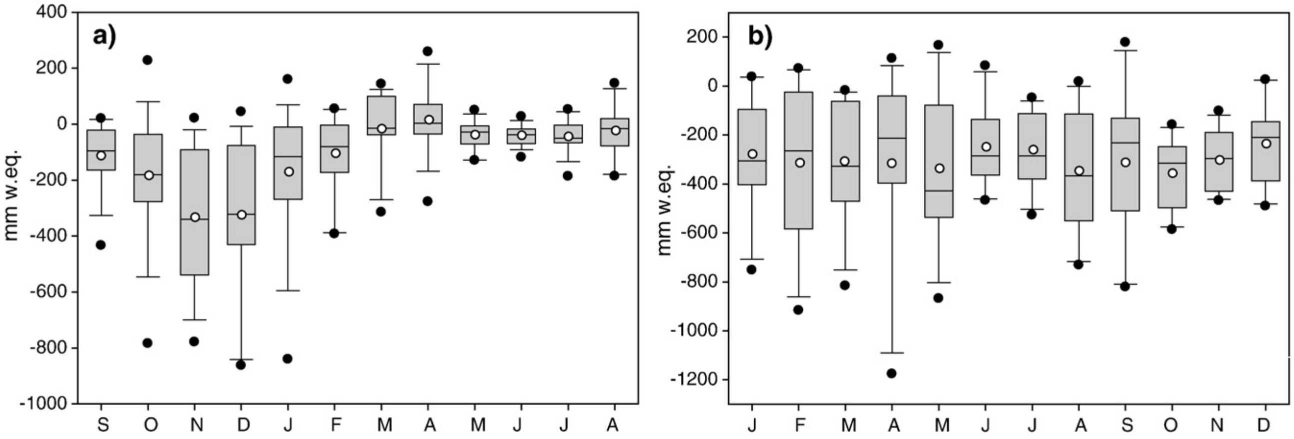

Fig. 8. Whisker box plots of monthly mass balance for a) Chacaltaya (data from Sept. 1991 to April 2005) and b) Antizana (data from Jan. 1995 to Dec. 2005). Plots show monthly minimum and maximum (black dots), 10th and 90th percentile (error bars), 25th and 75th percentile (gray box), median (horizontal line) and average (white dot). Note that scale on y-axis is different for a) and b).

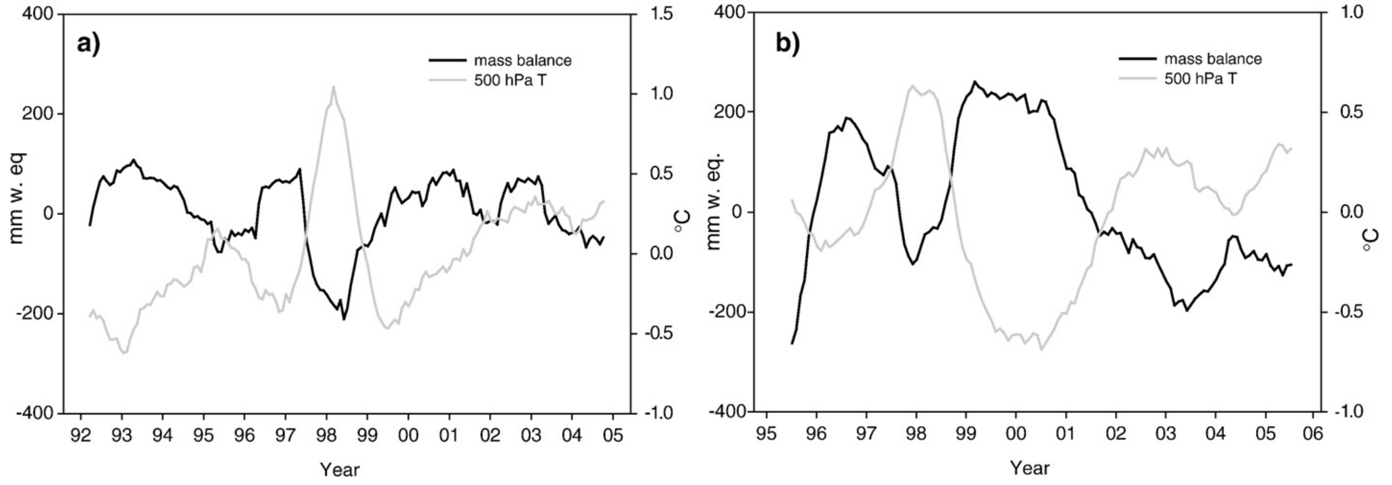

Fig. 9. Time series of monthly mass balance anomalies and 500 hPa temperature anomalies for a) Chacaltaya (Sept. 1991–April 2005) and b) Antizana (Jan. 1995–Dec. 2005). NCEP–NCAR 500 hPa temperature data was extracted from grid cells closest to glaciers (15°S–17.5°S/67.5°W for Chacaltaya and 0°/77.5°W for Antizana). Both time series have been smoothed with a 12-month running mean.

temperature variations (Fig. 9b). Here however, the impact of temperature appears to be more direct through changes in the snow–rain line, which reduces accumulation in the lower zone of the glacier, exposes the snout to rain as opposed to snow and thereby lowers the albedo (Favier et al., 2004a; Francou et al., 2004).

In the Cordillera Blanca, mass balance is also dependent on the phase of ENSO, but the influence is generally not as strong. Kaser et al. (2003) and Vuille et al. (2008) found a significant relationship between ENSO and reconstructed glacier mass balance using a 41-year long mass balance time series, but they also pointed out that this relationship does not hold in all years. Because the teleconnection mechanism linking ENSO with precipitation is spatially unstable and oscillates latitudinally, it affects the Cordillera Blanca in most, but not all ENSO years (Vuille et al., 2008).

4.3. The processes driving mass balance — the surface energy balance (SEB)

The SEB quantifies the amount and direction of the various energy fluxes from and to the glacier surface and thereby describes the processes which can explain the observed mass balance — climate correlations discussed in the previous section. A detailed SEB can only be established through accurate measurements on the glacier itself, which requires the installation and maintenance of automated weather stations (AWS) for a period long enough to properly understand diurnal and seasonal cycles, as well as interannual variations. Such detailed monitoring programs are relatively new and therefore, until recently, energy balance studies instead focused on quantifying the amount of energy needed to produce an observed change in glacier mass balance (sensitivity studies). Here we first discuss results from early sensitivity studies (Section 4.3.1) and then present more recent analyses from SEB measurements (Section 4.3.2).

4.3.1. Sensitivity studies

Some of the earliest sensitivity studies were performed by Hastenrath and Ames (1995b) in the Cordillera Blanca. They estimated the average surface lowering on Yanamarey glacier between 1977 and 1988 to be 1.5 m yr^{-1}. Given the latent heat of melting, $L_m = 33.4 \times 10^4$ J kg^{-1}, the energy required to produce such a change corresponds to a positive energy balance (directed toward the glacier) of 16 W m^{-2}. Sublimation, which is much more energy-consuming (latent heat of sublimation $L_s = 283.4 \times 10^4$ J kg^{-1}) was neglected by the authors in their study. In theory, albeit unrealistic, the easiest way to account for this change in glacier thickness is through a decrease in precipitation by the amount of imbalance, in this case, 1.5 m. Alternatively Hastenrath and Ames (1995b) calculated that a cloudiness decrease of 10%, a temperature increase of 2 °C, a specific humidity increase of less than 1 g kg^{-1} or any combination of the above, could have led to the observed glacier thinning. On Uruashraju glacier Ames and Hastenrath (1996) estimated an average surface lowering of 1.04 m yr^{-1} between 1978 and 1988, equivalent to an energy surplus of 12 W m^{-2}. Their calculations suggested that the energy increase could have been produced by a cloudiness decrease of less than 10%, a temperature increase of 1.5 °C, an increase in specific humidity of less than 1 g kg^{-1} or any combination of these (Ames and Hastenrath, 1996). Kaser et al. (1996a) performed a similar sensitivity study in the Cordillera Blanca, calculating the energy surplus responsible for the observed ELA rise of 95 m between 1920 and 1970. According to their results either a temperature increase of 0.51 °C, a precipitation decrease of 1177 mm, a global radiation increase of 1.076 MJ m^{-2} d^{-1} or an increase in evaporation of 157 mm yr^{-1} could have caused the change in ELA position. Comparing their results with actual observed changes in climate, Kaser et al. (1996a) concluded that a temperature increase could only explain about half of the observed rise in ELA and that precipitation changes were too small to have had a significant impact, consistent with observations by Vuille and Bradley (2000) and Vuille et al. (2003a). The remaining half of the observed ELA change was therefore attributed to a combined effect of the remaining factors. Similarly Kaser and Georges (1997) attributed the observed ELA increase in the northern Cordillera Blanca between 1930 and 1950 only in part to a temperature increase, but more so to decreased humidity and its indirect effects of reduced precipitation, reduced cloud cover and hence increased incoming radiation. They also observed large differences in ELA rise across the Cordillera Blanca from east to west and argued that this differential ELA rise was inconsistent with a temperature forcing, which should have had a similar impact throughout the region. Mark and Seltzer (2005a) performed a similar sensitivity analysis on Nevado Queshque, also in the Cordillera Blanca, to assess the causes of the observed ice thinning (353 mm yr^{-1}) between 1962 and 1999. Assuming that 20% of the mass loss was due to sublimation and the remaining 80% due to melt, they concluded that 9.3 W m^{-2} was required to produce the observed mass loss. According to their results this energy surplus was most likely caused by a temperature rise of 1 °C, combined with a specific humidity increase of 0.14 g kg^{-1}, as this scenario was most in line with actual observed changes in climate over this period. They also pointed out that this estimate was inconsistent with the observed average ELA rise of only 72 m, which they explained with the fact that the glaciers are not in equilibrium and lag behind the climate forcing. On Chacaltaya glacier Ramirez et al. (2001) estimated that an average increase in heat supply of 10 W m^{-2} was responsible for the excess melting since 1983 (assuming no sublimation). According to their calculations it would require a ~200 m drop in the ELA to counterbalance this increase in heat supply and to again stabilize the glacier. Such a scenario would bring the ELA down to a level near 5220 m, close to the average ELA in the period 1940–1963, before accelerated glacier recession began (Francou et al., 2005).

Another, rather simple but effective way to qualitatively attribute observed changes in glacier extent to various climate forcings, is to assess how the glacier geometry changes over time and where glaciers tend to lose the most mass. For example if changes in cloudiness and hence solar radiation were the main cause of changes in glacier extent, one would expect to see a differential thinning in accordance with the radiation geometry of the glacier (e.g. Mark and Seltzer, 2005a,b). While tropical Andean glaciers do indeed reside preferentially in locations that receive less short-wave radiation than non-glacierized areas at similar elevation (Klein et al., 1996), there are no studies indicating that a preferential thinning has taken place on tropical Andean glaciers, which could be attributed to changed radiation receipts.

4.3.2. SEB studies based on energy flux measurement

While the sensitivity studies discussed above are very interesting and insightful in their own right, they fall short of clearly attributing observed changes in glacier mass and extent to one or several factors. There is always a variety of potential combinations which could explain the energy imbalance at the glacier surface. The only way to solve this problem is to measure all the relevant fluxes at the surface over a long enough period of time. The surface energy balance (SEB) of a melting ice surface can be written as:

$$\mathrm{SW}^{\downarrow}(1-\alpha)+\mathrm{LW}^{\downarrow}+\mathrm{LW}^{\uparrow}+H+C+P+L_{\mathrm{s}}S+L_{\mathrm{m}}M=0$$

where $\mathrm{SW}^{\downarrow}$ is the incoming short-wave radiation, α the surface albedo (reflectivity), $\mathrm{LW}^{\downarrow}$ and $\mathrm{LW}^{\uparrow}$ the incoming and outgoing long-wave radiation respectively, H the turbulent sensible heat flux, C the subsurface conductive heat flux, P the heat supplied by precipitation and L_{s} S *sensu stricto* the turbulent latent heat flux and L_{m} M the mass consuming terms, with L_{s} and L_{m} the latent heats of sublimation and melt respectively and S and M the rates of sublimation and melt. All energy fluxes are considered positive if directed toward the surface and negative if they are directed away from it. C and P are negligible compared to the other terms of the SEB (e.g. Wagnon et al., 2001; Favier et al., 2004b). All these terms in turn depend on a number of climatic factors. $\mathrm{SW}^{\downarrow}$ for example depends largely on cloud cover, α is controlled by the amount and timing of snowfall and $\mathrm{LW}^{\downarrow}$ depends on atmospheric temperature and moisture content, $\mathrm{LW}^{\uparrow}$ depends on surface temperature and H depends on the vertical gradient of air temperature and wind velocity. The mass consuming term (latent heat flux) L_{s} S is controlled by the vapor pressure gradient between the glacier surface and the air above, which in turn is related to surface temperature, air humidity and wind speed.

The terms of the equation also show pronounced seasonality on tropical and especially outer tropical glaciers, with very different behavior during dry and wet seasons. $\mathrm{SW}^{\downarrow}$ for example is potentially higher during the wet season due to higher solar inclination, but at the same time it is modulated due to increased cloud cover. Albedo α is generally very high during the wet season due to frequent snowfall. $\mathrm{LW}^{\downarrow}$ and $\mathrm{LW}^{\uparrow}$ almost cancel each other, H is reduced due to low wind speeds and sublimation is reduced because of the high humidity and low wind speeds. This effectively means that most of the surplus energy is consumed by melting, which is an ablation process 8.5 times more efficient than sublimation. As a consequence high melt and high accumulation during the wet season lead to a large mass turnover (e.g. Kaser et al., 1996b; Sicart et al., 2003; Kaser et al., 2005).

During the dry season on the other hand, the LW balance is negative due to low incoming long-wave radiation related to reduced cloudiness, and weak vertical gradients of air temperature and the large vapor pressure gradient lead to enhanced sublimation. As a result melting is reduced and mass turnover limited. Consequently tropical glaciers are highly sensitive to changes in atmospheric humidity (which governs sublimation), precipitation (whose variability, particularly during the rainy season induces a positive feedback on albedo), and cloudiness (which controls the incoming long-wave radiation).

Wagnon et al. (1999a,b) based on measurements from an AWS installed on Zongo glacier found a marked seasonality of mass loss and runoff that cannot be explained by the sensible heat transfer, which shows little seasonality and is generally small. Instead net all-wave radiation and the turbulent latent heat dominate the SEB. During the 2006 dry season for instance (Fig. 10b), albedo remains low (~0.35 corresponding to bare ice), leading to high net short-wave radiation, counter-balanced by a strongly negative long-wave balance (due to very low cloudiness reducing $\mathrm{LW}^{\downarrow}$). Consequently, net all-wave radiation is moderate and rather similar to what we observe during the wet season (Fig. 10a) where albedo is higher (~0.7 due to snow at the surface) leading to lower net short-wave radiation. The various terms of the SEB, averaged over the two 20-day periods, are listed in Table 1 for comparison. These measurements demonstrate that the incoming energy is quite constant throughout the year and that instead it is the partitioning of this energy into melt and sublimation, controlled by humidity, which causes the much higher mass loss during the wet season. For example sublimation consumed 63% of the total available energy during the hydrologic year 1996–97 to produce only 17% of the mass loss (Wagnon et al., 1999a). When humidity is high, the available radiative energy is directly consumed by melting (wet season), while the enhanced vapor pressure gradient and the stronger wind velocities during the dry season favor sublimation, thereby leading to reduced discharge. This shows how sensitive tropical glaciers are toward changes in specific humidity and that increasing humidity is an effective climate change scenario to enhance glacier retreat, at least in the outer tropics. These SEB calculations are consistent with mass balance measurements from stake networks, sublimation measurements using lysimeters and proglacial stream discharge measurements, thereby increasing the confidence in the results (Wagnon et al., 1999a; Sicart et al., 2005).

Interannual mass balance variations, such as the large mass loss during El Niño years, discussed in the previous section, can equally be explained with SEB measurements. The much larger mass loss on Zongo during the El Niño 1997/98 for example, was not directly linked to higher temperatures (and hence higher sensible heat flux), but to a significant precipitation deficit (Wagnon et al., 2001). This led to low-albedo bare ice exposed for a much longer time of the year and over a much larger glacier surface (the ELA was 450 m higher in 1997/98 than during the previous year). Absorption of short-wave radiation was therefore greatly enhanced and consequently the measured glacial runoff at the glacier snout was two thirds higher than normal (Wagnon et al., 2001). Decreasing precipitation (or changes in the phase or the timing of precipitation) is therefore also a very effective climate change scenario to enhance glacier retreat in the outer tropics.

Measurements on Antizana glacier in Ecuador reveal that the SEB in the inner tropics is equally governed by net all-wave radiation and hence albedo (Favier et al., 2004b). However, because of the absence of thermal seasonality, the ablation zone is exposed to oscillations of the 0 °C isotherm throughout the year. These small fluctuations in temperature determine the rain–snow line on the ablation zone and hence have a major impact on the albedo. Consequently air temperature significantly influences the energy balance through changes in albedo and net short-wave radiation receipts (Favier

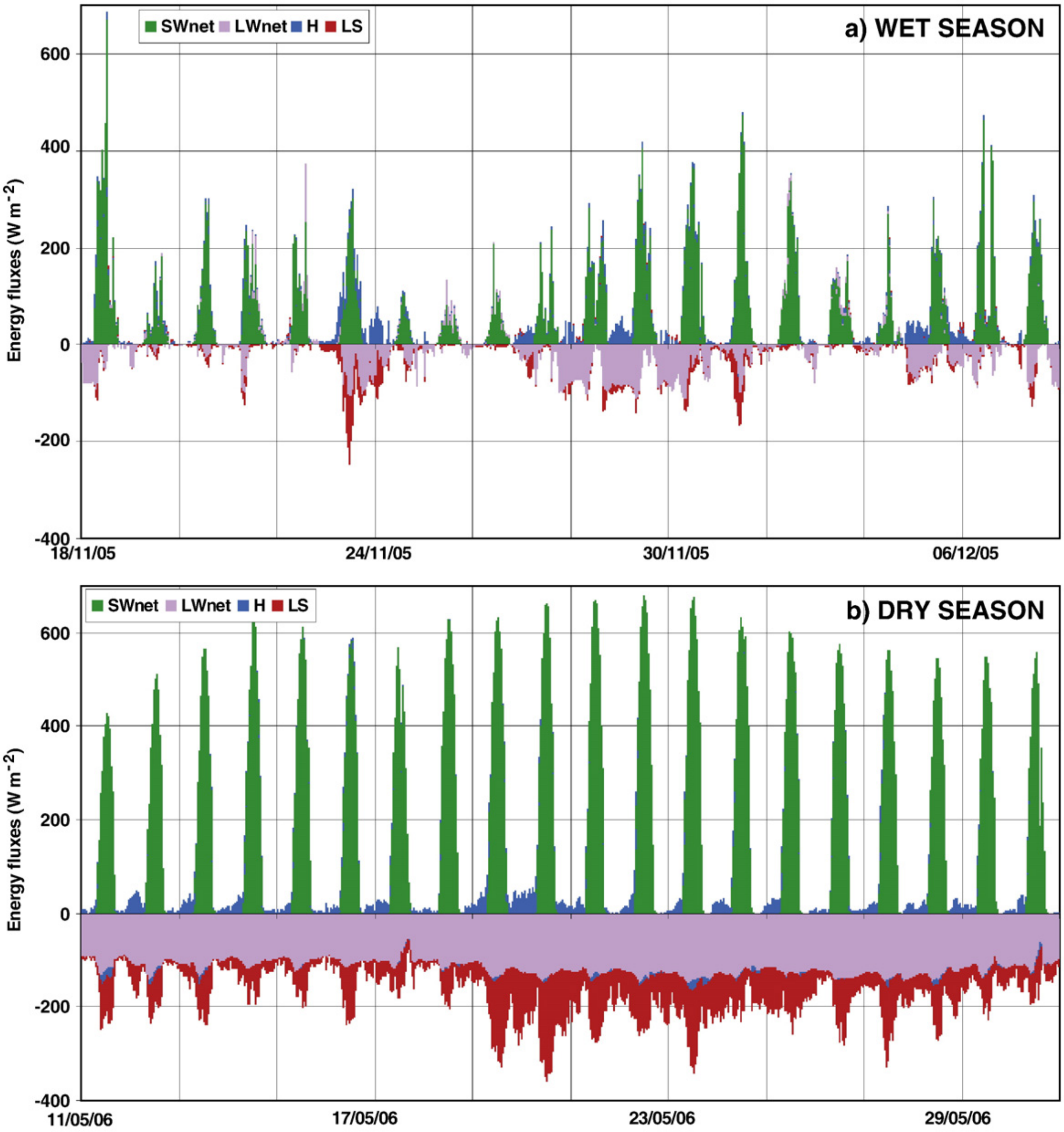

Fig. 10. Daily cycle of the various energy balance terms (net short-wave radiation SWnet, net long-wave radiation LWnet, turbulent sensible *H* and latent L_s heat fluxes) on Zongo glacier during two 20-day periods representative of a) the wet season and b) the dry season of the hydrologic year 2005–06.

et al., 2004a,b; Francou et al., 2004). Interannual variations of the SEB on Antizana are also strongly affected by the ENSO cycle. During El Niño, increased air temperature, which favors rain over snowfall, weak and sporadic snowfall, insufficient to maintain a high glacier albedo, low wind speeds, more favorable for melting than sublimation, and reduced cloud cover, which increases the incoming short-wave radiation, are the main factors affecting the SEB and causing high melt rates. La Niña events on the other hand are characterized by opposite climatic conditions, which reduce melting at the glacier surface (Francou et al., 2004).

Most SEB studies in the tropical Andes are based on melting surfaces in the glacier ablation zone. To date there is only limited information available on the energy balance from the accumulation zone at high altitude, where no melting takes place. Wagnon et al. (2003) performed some experiments and measured the SEB for a short time in austral winter near the summit of Illimani, at 6340 m in the Cordillera Real. Their results show that here the net all-wave radiation balance is mostly negative due to a constantly high albedo and the reduced $LW^{\downarrow}$, resulting from generally clear skies. Sublimation was estimated at ~1 mm w.e. d^{-1}, which is of the same order of magnitude as at lower elevations in ablation areas.

Table 1

20-day averages of the various terms of the SEB and meteorological measurements at the surface of glacier Zongo. The time periods correspond to the data shown in Fig. 10. See text and Fig. 10 for detailed explanation of terms

	11.–30. May 2006	18. Nov.–7. Dec. 2006
Rnet (W m^{-2})	36.3	31.3
u (m s^{-1})	3.0	2.2
Albedo	0.36	0.72
Relative humidity (%)	26.4	79.4
Air temperature (°C)	−3.6	0.8
H (W m^{-2})	7.9	8.1
L_s (W m^{-2})	−57.3	−6.4
Sublimation (mm w.e. d^{-1})	−1.8	−0.2

5. Future climate change and implications for glaciers and water resources

5.1. Projected 21st century climate change

Studies on future climate change in the tropical Andes and, more generally, South America, so far have focused exclusively on the two parameters temperature and precipitation. Because of the poor resolution of most GCMs the topography of the Andes is not adequately resolved and the projected temperature changes for the Andes are too low. Some studies have circumvented this problem by instead analyzing temperature changes in the free troposphere. Bradley et al. (2004) for example analyzed free tropospheric temperature changes along the American Cordillera based on simulations from 7 different General Circulation Models (GCMs), forced with $2\times CO_2$ concentrations. Compared with control runs the temperature changes were large and increased with elevation to reach 2.5–3 °C in the tropical Andes after CO_2 doubling. In a follow up study Bradley et al. (2006) investigated how annual free-air temperatures changed in 8 different GCMs between 1990–1999 and 2090–2099 along that same transect from Alaska to Patagonia in IPCC-scenario SRES A2. The results indicate a continued warming of the tropical troposphere throughout the 21st century, with a temperature increase that is again enhanced at higher elevations (Fig. 11). By the end of the 21st century, following this high-emission SRES A2 scenario, the tropical Andes will experience a massive warming on the order of 4.5–5 °C. (Fig. 11d). Analyses of changes in surface temperature show that tropical South America will warm more (by 3–4 °C in the SRES A2 scenario) than the southern part of the continent (Boulanger et al., 2006). However, while all emission paths tend to show the same pattern of warming, they differ significantly in amplitude. While SRES A1B reaches about 80–90% of the warming displayed in the SRES A2 scenario at the end of the century, the more moderate (and optimistic) SRES B1 path displays only about half of the warming of SRES A2 (Boulanger et al., 2006).

Most models used for the IPCC-AR4 report predict an increase in precipitation in the tropical Andes during the wet season and a decrease during the dry season, effectively enhancing the seasonal hydrological cycle (Vera et al., 2006). The spatial pattern of change is quite similar for all emission scenarios, but again the amplitude of the change is much stronger in the A2 scenario, than in A1B and B1 (Boulanger et al., 2007). However, intra-model differences are much larger for precipitation than for temperature.

The projected changes in temperature will likely affect the inner tropical glaciers more than glaciers in the outer tropics. Glaciers in Ecuador for example are very sensitive to changes in temperature, as the rise of the 0 °C isotherm has an immediate impact on the rain–snow line and thus on albedo and the net radiation balance (Favier et al., 2004b). This impact is seen interannually through the immediate and severe impact of El Niño events on the net mass balance (Francou et al., 2004). In the outer tropics, changes in temperature are generally less relevant, given that glaciers are mostly located above the freezing line. In fact, the difference between the ELA and the 0°-isotherm, which is a good indicator of the sensitivity of tropical glaciers to global warming (Favier et al., 2004a), rises significantly from below 0 (i.e. the 0°-isotherm is above the ELA) in the inner tropics to several hundred meters in the outer tropics of Bolivia or northernmost Chile (Kuhn, 1980). Glaciers in the outer tropics therefore may be more easily affected by changes in precipitation, as it governs the albedo and the radiation balance (Francou et al., 2003). A mid-tropospheric warming of several °C, as projected in Bradley et al. (2006), of course will impact glaciers throughout the tropical Andes. Nonetheless it is important to keep in mind that glaciers may respond differently (both in sign and magnitude) to changes in temperature, precipitation, humidity and cloud cover, depending on their location and their sensitivity to certain climate parameters.

5.2. Implications for water resources

Given the projected future changes in climate and the high sensitivity of tropical glacier mass and energy balance to climate change, negative impacts on glacier mass balance will be felt throughout the Andean Cordillera. Glaciers will retreat and many will completely disappear, with significant consequences for local populations. It is likely that the change in streamflow, due to the lack of a glacial buffer during the dry season, will significantly affect the availability of drinking water, water for hydropower production, mining and irrigation (e.g. Barry and Seimon, 2000; Barnett et al., 2005; Francou and Coudrain, 2005; Bradley et al., 2006; Diaz et al., 2006; Vuille, 2006; Vergara et al., 2007). In the tropical Andes this problem is exacerbated when compared with mid-latitude mountain ranges, such as the Rockies or the Alps, because ablation and accumulation seasons coincide, which precludes the development of a long-lasting seasonal snow cover outside the glaciated areas. Glaciers are therefore the only major seasonally changing water reservoir in the tropical Andes, as demonstrated by the high correlation between a catchments' capacity to store precipitation and its percentage of glaciated area (Kaser et al., 2003, 2005).

The potential impact of glacier retreat on water supply for human consumption, agriculture and ecosystem integrity is of grave concern (Buytaert et al., 2006; Young and Lipton, 2006). On the Pacific side of Peru most of the water resources originate from snow and ice in the Andes. Many large cities in the Andes are located above 2500 m and thus depend almost entirely on high altitude water stocks to complement rainfall during the dry season. Hydropower constitutes the major source of energy for electricity generation in most Andean countries and a growing population with increasing water demands further aggravates the problem. Furthermore, as glaciers have retreated and lost mass, they have added to a temporary increase in runoff (Mark et al., 2005; Mark and McKenzie, 2007). This increase will not last very long, as the frozen water stored in glaciers diminishes. Yet downstream users are quickly adapting to enhanced water availability and plan future development accordingly, which raises sustainability concerns (e.g. Mark, 2008).

There are signs emerging that these are not just future runoff scenarios but real changes which are already taking place. On Yanamarey glacier in the Cordillera Blanca for example, an increase in stream discharge due to glacier thinning was already noted in the 1980s. Later studies concluded that about half of the mean annual glacier water discharge of ~80 l s^{-1} is supplied by non-renewed glacier thinning (Hastenrath and Ames, 1995b). Similar studies on nearby Uruashraju glacier confirmed these numbers (Ames and Hastenrath, 1996) and raised concern about the future water supply in the Rio Santa valley downstream. Today it is estimated that 30–45% of the discharge in the two Rio Santa subcatchments Yanamarey and Uruashraju is from non-renewed glacier melt (Mark and Seltzer, 2003). Over the most recent measurement period, 2001–2004, this number increased to 58% in the Yanamarey subcatchment, up from 35% in 1998–99 (Mark et al., 2005). If applied to the entire Rio Santa watershed, which drains the western side of the Cordillera Blanca, this value is still 10–20% (Mark and Seltzer, 2003). To make matters worse, the number is considerably higher (~40%) during the dry season, when water is most needed (Mark et al., 2005). This situation raises a number of serious sustainability concerns, especially in the light of the rapidly increasing population in the valley (Kaser et al., 2003).

When future water shortages will become acute depends not only on which climate change scenario will unfold, but also on the site-specific response of glacierized catchments to climate change, as has been demonstrated by a couple of recent modeling studies. In one approach Pouyaud et al. (2005) applied a uniform and very conservative linear warming rate of only ~1 °C per century, to simulate the runoff coefficient for several catchments in the Cordillera Blanca until the year 2300. According to their results, runoff will continue to increase for another 25–50 years in these catchments before a decrease eventually sets in. These results, however, should be interpreted

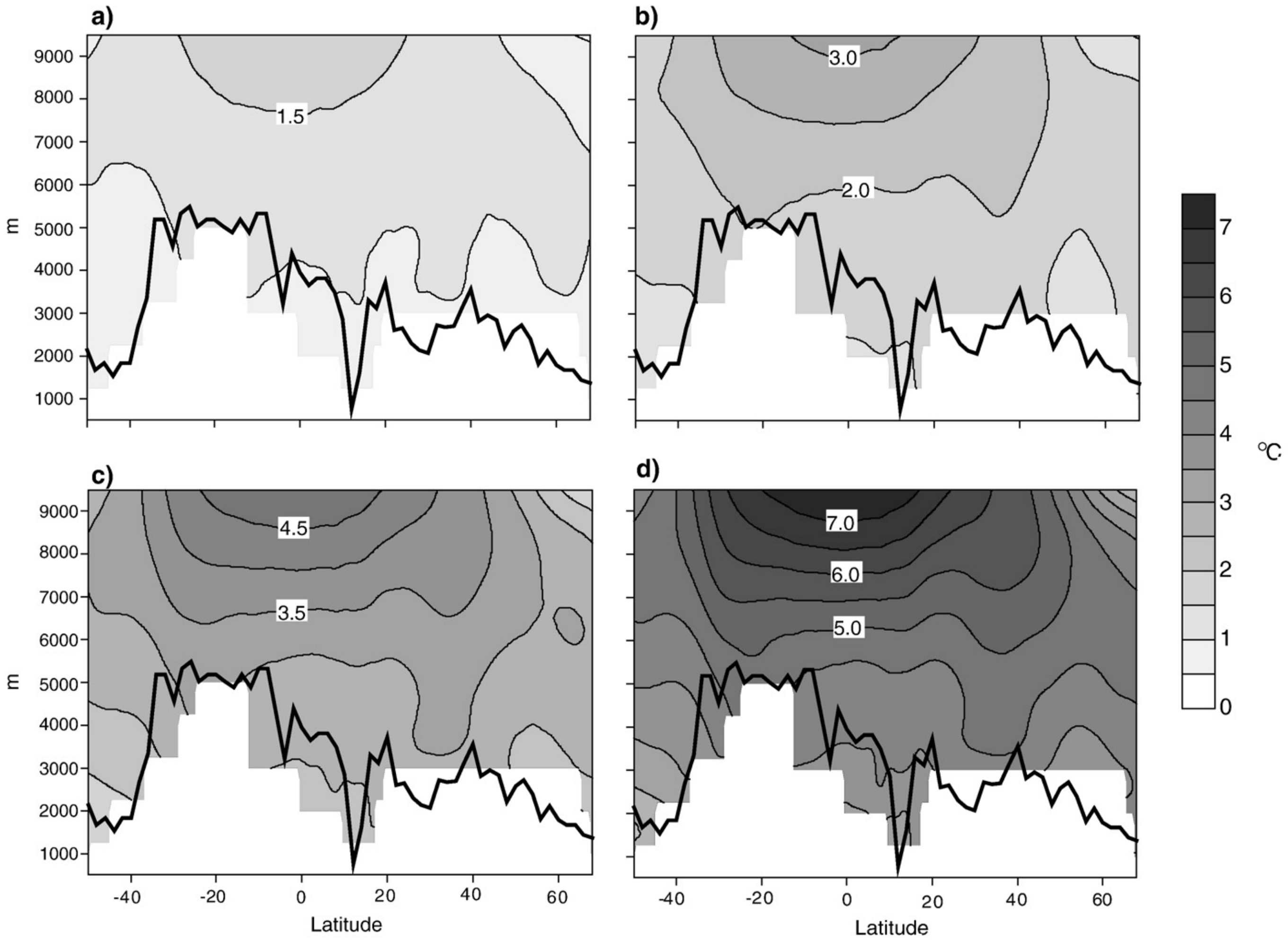

Fig. 11. Projected changes in mean annual free-air temperature for a) 2026–2035, b) 2046–2055, c) 2066–2075 and d) 2090–2099. All Panels show departure from 1990–1999 average along a transect from Alaska (68°N) to Patagonia (50°S), following the axis of the American Cordillera mountain chain. Results are the mean of eight different general circulation models used in the 4th assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) using CO_2 levels from scenario SRES A2. Black line denotes mean elevation along transect; white areas have no data (surface or below in the models).

cautiously as the glacier evolution in their model depends solely on temperature, assuming that sensible heat transfer alone can adequately represent the energy balance of a tropical glacier. Juen et al. (2007) used a more sophisticated approach to assess how the seasonality of runoff in the Cordillera Blanca changes, by using a tropical glacier-hydrology model (ITGG 2.0-R). The model was first calibrated over a ten year period (1965–75) and then validated with independent runoff measurements. Next changes in future runoff characteristics were simulated based on four different IPCC scenarios (A1, A2, B1 and B2). These simulations are all based on the respective steady-state of the glacier, i.e. the glacier area is gradually reduced until, under the new climate background conditions, the specific mass balance is zero. Dynamic effects and response times, however, are not accounted for and therefore this approach excludes an exact prediction in time. As expected, glacier volume is significantly lowered in all scenarios, but glaciers do not disappear completely. In the Llanganuco catchment for example, which is 31% glaciated today, a new steady-state glacier in 2050 has an extent that is reduced somewhere between 38% (B1, 'best case' scenario) and 60% (A2, 'worst case' scenario), when compared to 1990. By 2080 these values increase to a 49% (B1) to 75% (A2) reduction in glacier size (Juen et al., 2007). Consequently, dry season runoff is significantly reduced, in particular in the A2 scenario. During the wet season, however, runoff is higher, which can be explained by the larger glacier-free areas and therefore enhanced direct runoff. Similar results are found when this approach is extended to other catchments in the Cordillera Blanca (Fig. 12). In general it appears that the overall discharge may not change very much, but that the seasonality intensifies significantly. Fig. 12 also clearly demonstrates that climate change will affect glacier extent and hence runoff behavior differently in the various catchments, depending on their percentage of glaciated area, catchment hypsometry, etc. In general the predicted changes in runoff seasonality are larger in catchments where the degree of glaciation is high. In several of these catchments the impacts under the A2 scenario are more severe than in the example from Llanganuco. The Pachacoto catchment for example will be ice free by 2080 under the A2 assumption and Quilcay and Paron will have lost 92% and 95% of their glacier extent respectively (Juen, 2006). In this context, it is noteworthy that the results of A2 are much more dramatic in 2050 than they are 30 years later, in 2080 under the more moderate B1 scenario (Fig. 12). These results illustrate how uncertain the future extent of glaciation and therefore the changes in runoff really are, depending on which emission path we will ultimately follow. Since the IPCC explicitly refrained from assigning likelihoods to these emission scenarios, no single outcome is more probable than the others, but the results from Fig. 12 can certainly put some upper and lower bounds on the changes that are to be expected 50–80 years from now.

In the Cordillera Real, Bolivia, the situation is generally similar as portrayed above for the Cordillera Blanca. On Zongo glacier proglacial

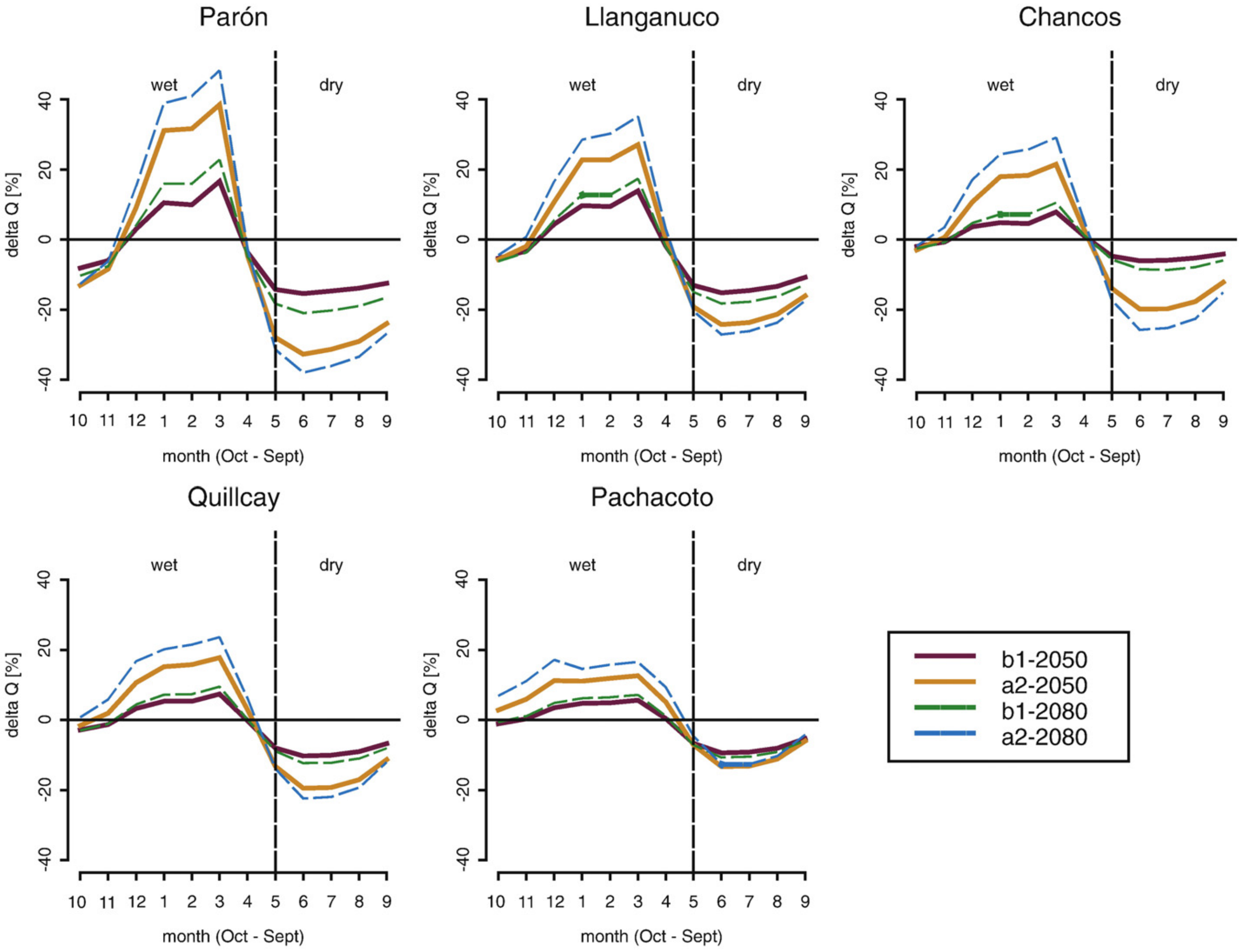

Fig. 12. Simulated change in monthly runoff in 2050 and 2080 (in %, compared with 1961–90 average) in 5 different catchments of the Cordillera Blanca based on the IPCC climate change scenarios B1 and A2. The catchments exhibit a decreasing degree of glaciation (1990 values): Paron 40.9%; Llanganuco 31.0%; Chancos 24.1%; Quillcay 17.4%; Pachacoto 9.7%.

runoff has been monitored since the early 1990s, with earlier gauge readings by an electric power plant going back to 1973 (Ribstein et al., 1995; Francou et al., 1995; Caballero et al., 2004). Measurements show that runoff is generally higher than catchment precipitation, indicating that the glacier is losing more mass than is being replenished through snow accumulation. On average a 410 mm annual deficit (1062 mm precipitation versus 1472 mm runoff) has been recorded between 1973 and 1993 (Ribstein et al., 1995). Sublimation was not accounted for in this study, which would have increased the deficit even further. Highest discharge occurs during warm El Niño years, despite dry conditions in those years. This is further confirmation for the role of glaciers as very efficient buffers, which tend to smooth runoff compared to precipitation, not just on seasonal time scales but also interannually (Ribstein et al., 1995, Francou et al., 1995).

6. Conclusions

The rapid retreat of tropical glaciers and the projected changes in regional hydrology mandate that some practical measures to adapt and prepare for future changes in runoff behavior (e.g. conservation, shift to less water-intensive agriculture, creation of water reservoirs, etc.) should be implemented without delay (see Bradley et al., 2006 and Vergara et al., 2007). However, it is also clear that much remains unknown and significant scientific progress needs to be made. In order to monitor the ongoing changes in climate and cryosphere, a much better network is needed, which does not only focus on certain target areas, but provides for an actual connected network of sites along climatic gradients from north to south as well as across the Andes from east to west (Francou et al., 2005; Coudrain et al., 2005; Kaser et al., 2005; Casassa et al., 2007). Despite the logistic difficulties, large glaciers must also be monitored, probably based on new techniques such as repeated laser scanning (i.e. Keller et al., 2007). A high-elevation observational network of automated weather stations is needed to monitor climate change at the elevation of the glaciers and not simply at low elevations, where the changes are likely to be much less dramatic (Bradley et al., 2004). Moreover, improved stream discharge gauging is needed to quantify the net hydrologic yield of glacierized watersheds. Many of the weather stations and stream gauges currently operating were installed in the middle of the 20th century, and lack technical maintenance (Mark and Seltzer, 2005b). They are old and outdated and need to be replaced with more up-to-date instrumentation. The available observational network is inadequate to accurately monitor and document the rapid changes taking place at high-elevation sites in the tropical Andes. Networks of mass and energy balance measurement sites are important and needed but they are also costly, labor-intensive and by their very nature limited in space. They should therefore be complemented by increased use and application of available remote sensing techniques and data sets from space. New advances in combining digital elevation models, SRTM data, GPS and satellite data such as Landsat, ASTER and SPOT, offer the opportunity to give a more detailed large-scale picture of changes in both the atmosphere and the cryosphere. While they are no substitute for on-site measurements, they can provide a much needed complementary picture. The Peruvian Andes, for example have been selected as a priority site to monitor glaciers with ASTER data under the Global Land Ice Measurements from Space (GLIMS) umbrella (Mark and Seltzer, 2005b; Raup et al., 2006).

Apart from the needed improvements in on-site and remote monitoring, it has also become increasingly clear that we need better and more detailed scenarios of future climate change in this region of steep and complex topography. Output from GCMs can at best provide us with a broad-brush perspective. High-resolution regional climate models, which allow for a better simulation of climate in mountain regions, coupled with tropical glacier-mass balance models, such as the one used by Juen et al. (2007) will help us to better understand and predict future climate changes and their impacts on tropical Andean glaciers and associated runoff. By running ensemble simulations under different SRES emissions paths we can define a probability distribution of what encompasses the most likely climate change outcome. Vuille (2006) recently proposed such a modeling strategy, which should allow us to establish robust projections of how glaciation and runoff will change in this region at the end of the 21st century.

Finally it is equally vitally important that greater collaboration and integration, and more information and data-sharing between agencies and institutions take place (Mark and Seltzer, 2005b). A number of recent workshops have tried to address this issue and to provide a starting point for such a collaborative network (Francou and Coudrain, 2005; Diaz et al., 2006; Casassa et al., 2007). This improved collaboration, in order to be truly relevant, should not be limited to scientific discussion and debate, but needs to include exchange with, and training of, local scientists, stakeholders and decision makers. A successful training course in mass balance measurements for example, was organized in La Paz in 2005 by IRD, the International Commission on Snow and Ice (ICSI) and UNESCO (Francou and Ramirez, 2005). As outlined by Young and Lipton (2006) there is often a scale-related disjuncture between scientific and technical studies examining hydrologic resources, the national institutions involved in water management and the demands and needs of the local population. One of the challenges to scientists is therefore to provide scientific information which is not only scientifically relevant but also socially applicable (Mark, 2008). Likewise, an often tragic history of living in proximity to Andean glaciers has highlighted the disproportionate impacts of climate-forced changes on local communities, demonstrating the need for scientific understanding to be integrated with local perceptions to formulate effective adaptation strategies (Carey, 2005). On the other hand, adequate mitigation and adaptation strategies can only be put in place with a better and much more detailed scientific knowledge on how future climate change will affect glaciological and hydrological systems in the Andes.

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