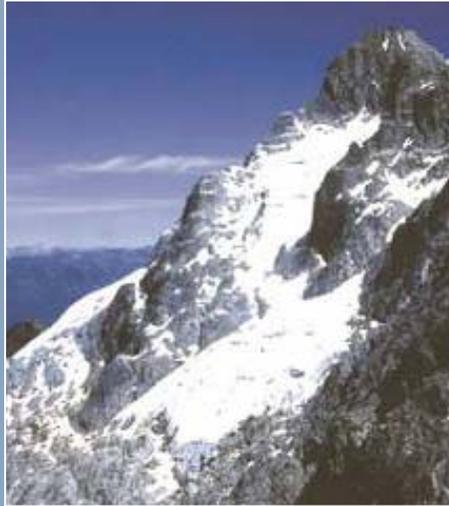
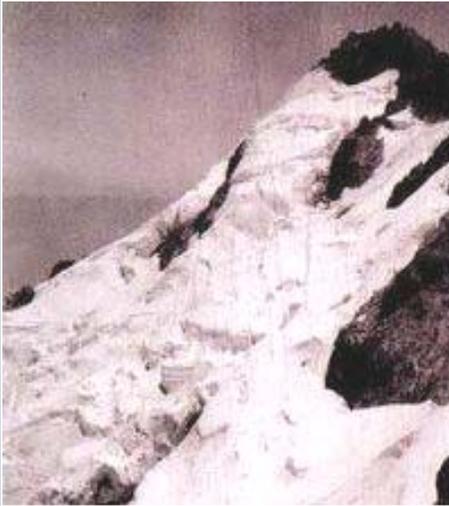


# CLIMATE CHANGE AND TROPICAL ANDEAN GLACIER RETREAT



**Eric Franquist, Dana McGlone & Mathias Vuille**  
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prepared by

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Cover photos:

Top row: Glacier Espejo (Pico Bolivar, Venezuela) in 1910 (left), 1988 (center) and 2008 (right)  
(Jahn, 1931; Schubert, 1992, 1999)

Bottom row: Glacier Chacaltaya, Bolivia 2002 and 2009 (Ramirez et al., 2001, Francou et al.,  
2003)

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## Summary

The extent of glaciers in the tropical Andes of Venezuela, Colombia, Ecuador, Peru and Bolivia is characterized by rapid shrinkage throughout the 20<sup>th</sup> century. Rates of recession have only increased with time and were most notable toward the end of the century. Increased ablation has been linked to climate change over the region with changes in temperature, precipitation, atmospheric circulation, convective cloud cover, and humidity. Temperatures in the northern Andes have increased by about 0.8°C during the 20<sup>th</sup> century at a rate of 0.11°C per decade from 1939 to 1998. This rate has more than tripled in the last 25 years of the 20<sup>th</sup> century. Precipitation trends have been more difficult to obtain, however, there are indications of a trend toward increased precipitation north of ~11°S, in Ecuador, northern and central Peru on annual time scales and at the peak of the austral summer precipitation season (DJF). In southern Peru and along the Peru/Bolivia border, most stations show a precipitation decrease. These changes have been linked to recent anomalous behavior of the Hadley circulation over the region, with enhanced convective activity over the tropics and enhanced subsidence over the subtropics. Given that glacier retreat is prevalent throughout the region regardless of precipitation trends suggests that temperature changes are the main factor negatively affecting glacier mass balance. Tropical glaciers are sensitive to changes in temperature not only through changes in sensible heat and higher melt rates but also because changes in freezing levels directly impact the rain-snow line and accumulation, albedo and the net radiation balance.

Projections for the 21<sup>st</sup> century indicate a continued warming of the tropical troposphere that is enhanced at higher elevations. The Special Report on Emissions Scenarios (SRES) A2 pathway indicates a potential warming on the order of 4.5-5°C by the end of the 21<sup>st</sup> century. Precipitation is expected to increase during the wet season in the inner tropics and decrease during the dry season, but uncertainties in precipitation projections are large. Over the southern tropical Andes (the Altiplano region) models suggest a strengthening of the upper tropospheric westerly zonal winds which would lead to a decrease in moisture transport and hence precipitation in the region.

Glacier retreat can have a profound impact on inhabitants of the Andes. Streamflow, for example has already decreased in some regions as glaciers have shrunk and been unable to store previous levels of precipitation. During the dry season, water shortages affect the irrigation of crops and the health of livestock. Increased tension has been displayed in some locales where local water users and mining companies using and potentially contaminating their limited water supply have opposing views regarding future water use allocation. Tourism has also been affected as glacial retreat has closed popular locations such as the Pastoruri glacier in Peru. Climate Change however, is not only affecting glacier extent but also has already lead to visible changes in biodiversity and ecosystem integrity along the Andes.

# 1. Introduction

More than 80% of the freshwater supply in the arid and semiarid regions of the tropics and subtropics originates in mountain regions, affecting more than half of the world's population (Messerli, 2001). Much of this water is stored as ice in glaciers and is gradually released over time. During the dry season, glacier runoff has been crucial to maintaining a more constant flow of freshwater throughout the year. Increased warming over the 20<sup>th</sup> century has led to glaciers in the tropical Andes increasingly being out of equilibrium with their current climate and rapid recession rates have been reported from many regions. The threat of changes in water supply as a result to these shrinking glaciers has received little attention as most in the climate community are focused on changes in the higher latitudes (Vuille et al., 2007). Reliable projections from global climate models (GCM's) have been hard to come by as these models have a coarse resolution, inadequate to simulate the steep and complex topography of the Andes. A strengthened focus on climate change impacts in the Andes is desperately needed as tropospheric temperature increases are expected to primarily affect higher elevations (Bradley et al., 2004, 2006) and be of similar magnitude as changes projected for the Arctic.

This paper intends to provide an up-to-date review of the recent literature regarding the effects of climate change on glaciers in the tropical Andes. First, observed trends in climate over the 20<sup>th</sup> century will be documented for various climate parameters. Next, a detailed review of past and present glacier extent in Venezuela, Colombia, Ecuador, Peru, and Bolivia will highlight the changes observed over the past century. Impacts of climate change and glacier retreat and projections of 21st century climate change will be discussed in the following sections using the most recent results from a variety of models following various IPCC-SRES scenarios. We end with a brief outlook and recommendations regarding future research and adaptation strategies for the region.

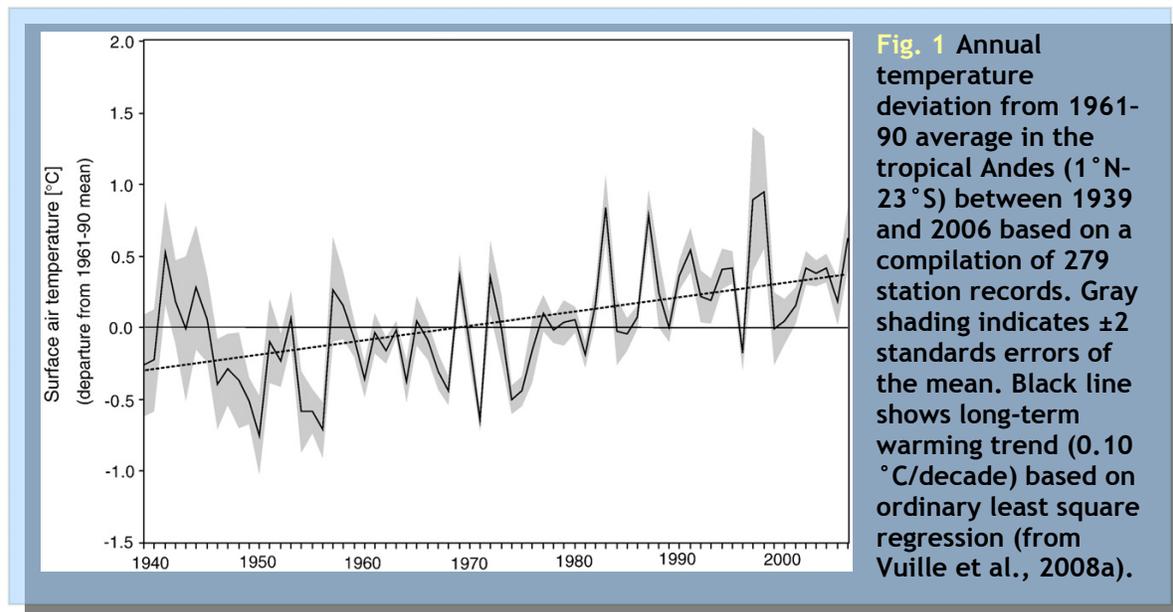
## 2. Observations during the 20<sup>th</sup> century

Glaciers in the tropical Andes are sensitive to changes in climate. An increase in the rate of glacial retreat in the 20<sup>th</sup> century has been documented (Vuille et al., 2008a). The following section will highlight some of the climate factors contributing to this glacier loss with a focus on the 20<sup>th</sup> century to the present, and then review the actual effects on glaciers in each country of the tropical Andes.

### 2.1. Observed Climate Change (1900-2011)

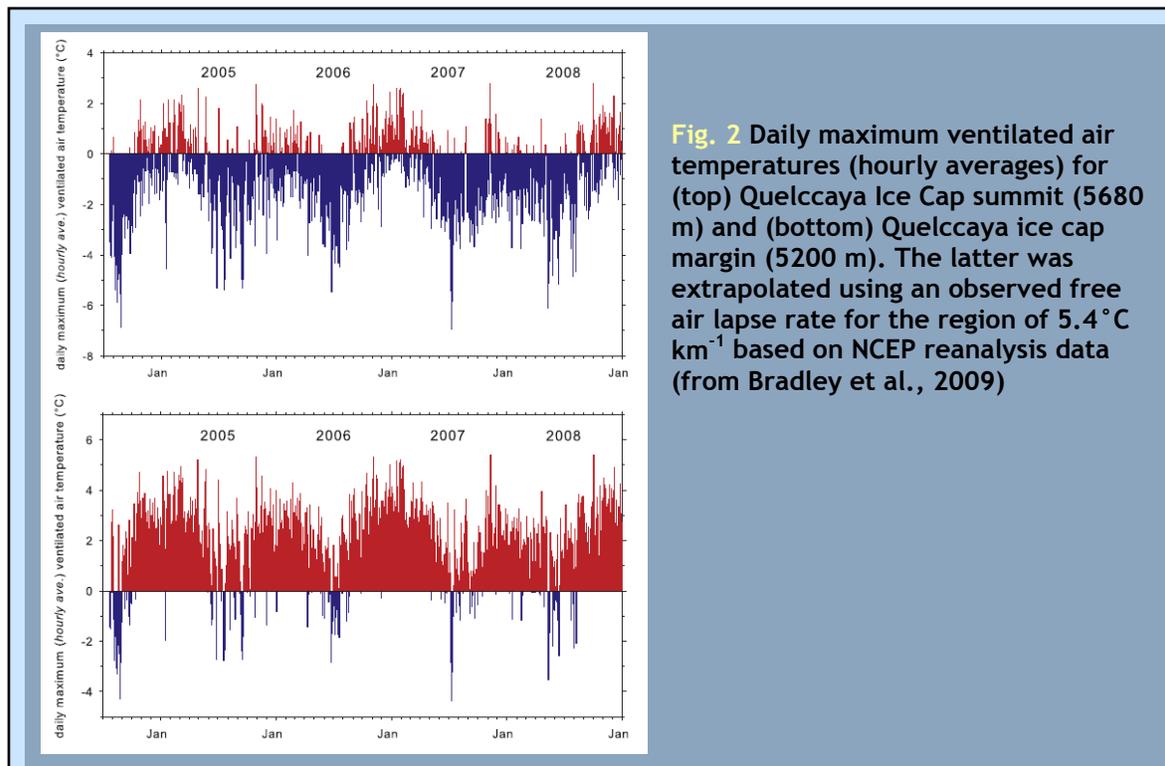
#### 2.1.1. Temperature

The mean annual temperature in the countries of the northern Andes (Venezuela, Colombia, Ecuador, and Peru) has increased by about 0.8°C during the 20<sup>th</sup> century (Marengo et al., 2011). A positive air temperature trend of 0.11°C per decade for the period from 1939-1998 was documented for the tropical Andes from 1°N to 23°S in relation to the 1961-1990 mean (Vuille and Bradley, 2000). This tendency has tripled over the last 25 years of the 20<sup>th</sup> century (0.32 - 0.34°C per decade), though some of the variability has been associated with the El Niño - Southern Oscillation (ENSO). Vuille et al. (2008a) performed an update to Vuille and Bradley (2000) through 2006 and found similar results with a warming trend 0.10°C per decade and an overall temperature increase of 0.68°C since 1939 (Fig. 1). A decreased rate of warming was found at surface stations at higher elevations in the Andes and especially along the lower eastern slopes. However, the trend toward increased temperatures is significant at the 95% confidence level, even at the highest elevations (Vuille and Bradley, 2000).



This overall warming trend has also been documented by several studies using other data sets. Diaz et al. (2003) for example analyzed changes in freezing level height over the American Cordillera and the Andes based on NCEP-NCAR reanalysis data and showed an increase of 53 m between 1958 and 2000. A regression analysis with the Niño-3 index revealed that a 1°C warming of tropical Pacific SST equals to about a 76 m rise of the freezing level height. Freezing level heights are important in the context of glacier variations since the mass balance of glaciers is critically dependent on the extent of ice melting and sublimation, and on the balance of snowfall versus rain, which affects albedo and net radiation (Bradley et al., 2009).

Other studies provide additional evidence of the warming trend toward the end of the 20<sup>th</sup> century on a more regional to local level. Racoviteanu et al. (2008) for example found significant warming trends in mean annual temperatures from 1970-1999 at three climate stations on the western side of the Cordillera Blanca. Mark (2002) and Mark and Seltzer (2005a) even documented a warming on the order of 0.35-0.39°C per decade between 1951 and 1999 in the same region. Bradley et al. (2009) measured temperatures on the summit of Quelccaya Ice Cap (5680 m) in southern Peru and revealed the frequent occurrence of daily maximum temperatures above freezing during the period from September-May each year (Fig. 2, top). Temperatures were obtained by ventilating the sensors prior to each measurement, to eliminate the effects of solar radiation. The observed temperatures were then projected to the ice cap margin (~5200 m) using the observed free air lapse rate for this site, 5.4°C km<sup>-1</sup> (Kistler et al., 2001). The results showed that daily maximum temperatures are now persistently above freezing for much of the year (Fig. 2, bottom).



**Fig. 2** Daily maximum ventilated air temperatures (hourly averages) for (top) Quelccaya Ice Cap summit (5680 m) and (bottom) Quelccaya ice cap margin (5200 m). The latter was extrapolated using an observed free air lapse rate for the region of 5.4°C km<sup>-1</sup> based on NCEP reanalysis data (from Bradley et al., 2009)

Quintana-Gomez (1997) detected an increase in both minimum and maximum temperatures between 1918 and 1990 in the central Andes of Bolivia. The trend for minimum temperatures was found to be much larger and effectively reduced the daily temperature range. Poveda and Pineda (2009) recorded a similar result in Pereira, Colombia, located around 1450 m a.s.l. on the western hills of Nevado del Ruiz and Santa Isabel glaciers during the period 1959-2007.

### *2.1.2. Precipitation*

Precipitation trends are less remarkable than changes in temperature. There are also fewer existing high-quality precipitation records which prevents an accurate analysis of any long-term trends (Vuille et al., 2008a). Vuille et al. (2003) used 42 station records to analyze trends in precipitation in the Andes of Ecuador, Peru, and Bolivia between 1950 and 1994. The results indicated a tendency for increased precipitation north of  $\sim 11^{\circ}\text{S}$ , in Ecuador, northern and central Peru on annual time scales and at the peak of the austral summer precipitation season (DJF). However, in southern Peru and along the Peru/Bolivia border, most stations show a precipitation decrease. It is important to note that while there does appear to be a regional signal, most of the individual station trends were insignificant. Of the 42 stations analyzed, only 5 (2) showed a significant increase (decrease) in the annual precipitation amount and elevation did not appear to impact the trend. Vuille et al. (2000a) did show notable precipitation increases over time along the eastern slopes of the Andes in Ecuador during the MAM rainy season. These results by Vuille et al., (2003) 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. Thibeault et al. (2010) identified a tendency toward a later onset of the wet season in the Bolivian Altiplano with less frequent but more intense rainfall.

### *2.1.3. Humidity*

Changes in humidity impact the mass balance of glaciers by partitioning the available energy into melt and sublimation (Wagnon et al., 1999). Melting has been found to increase with higher humidity. Vuille et al. (2003) studied the near-surface humidity changes in the Andes and found a significant increase in relative humidity between 1950 and 1995 of up to 2.5% per decade. The highest positive trend was in northern Ecuador and southern Colombia, while a more moderate increase (0.5-1.0% per decade) was found in southern Peru, western Bolivia and northernmost Chile. One can assume from the increased temperature and relative humidity trends that vapor pressure (or specific humidity) has increased significantly throughout the Andes as well. It

should be noted, however, that the CRU05 data used to document this trend are partially interpolated from synthetic data (New et al., 2000), and should be interpreted with great caution (Vuille et al., 2008b).

#### 2.1.4. Convective cloud cover (OLR)

Cloud cover is a very important variable to understand changes in the energy balance of tropical glaciers as it affects both incoming and outgoing short- and longwave radiation (Sicart et al., 2005). In the tropics cloud cover is predominantly of convective nature, in particular during the summer season when most of the glacier mass turnover occurs. One method of assessing changes in convective cloud cover is to measure the outgoing long-wave radiation (OLR) emitted by the earth's surface and the overlying atmosphere. This has been done by a number of polar orbiting satellites since 1974. OLR is sensitive to the height and amount of clouds over a particular region and time and has been used in numerous studies to evaluate 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., 2003). 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 cold, leading to low OLR values. Clear sky conditions lead to measured radiation from the earth's surface and the lower atmosphere which is warmer in the tropics and thus higher OLR values. In the absence of convective clouds, OLR is therefore affected by changes in surface temperature, low-level cloud cover, or water vapor content.

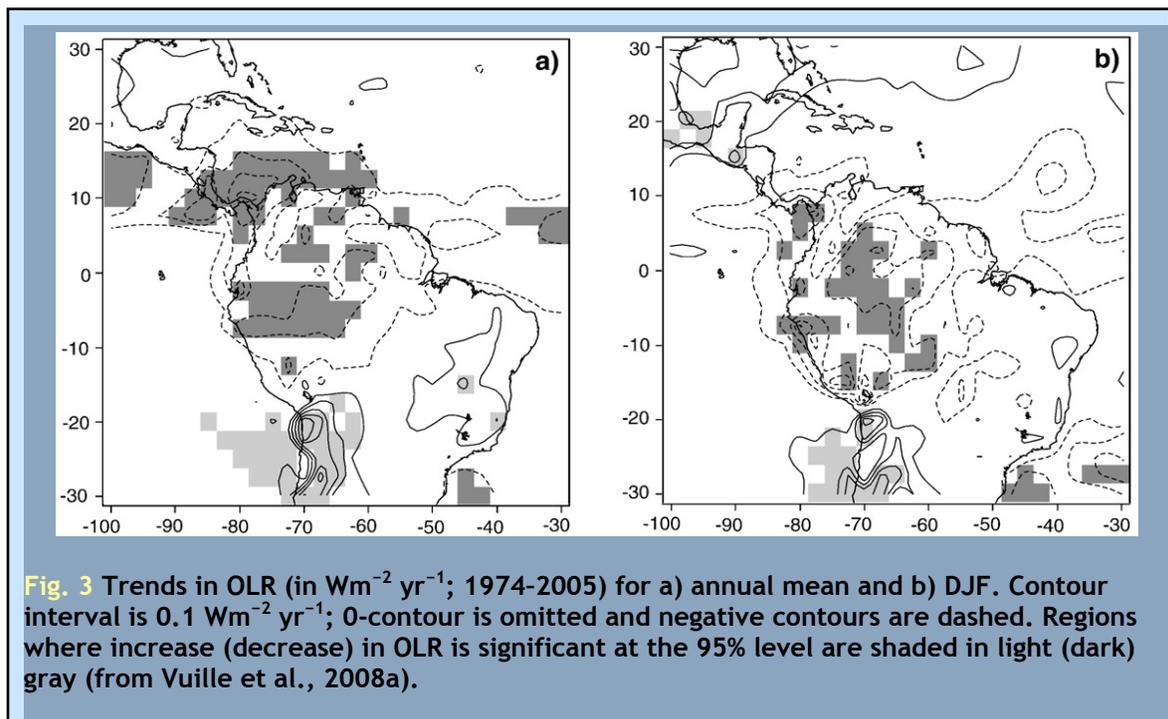


Figure 3 shows OLR trends between 1974 and 2005 with the largest trends occurring during austral summer, DJF, when OLR has significantly decreased over the tropical Andes and to the east over the Amazon basin. In the outer tropics (south of  $\sim 15^{\circ}\text{S}$ ) the pattern is reversed, showing an increase in OLR (Vuille et al., 2008a), consistent with the weak observed changes in precipitation (see section 2.1.2).

### *2.1.5. Atmospheric circulation*

Previously noted observations on precipitation and cloud cover suggest that the inner tropics are becoming wetter and cloudier while the outer tropics are getting drier and less cloudy. Changes in the meridionally overturning (regional Hadley) circulation could explain these trends with greater vertical ascent in the tropics and enhanced subsidence and clear skies in the subtropics. A recent study by Vuille et al., (2008a) did indeed detect such a pattern with increased ascent in a region around the equator from  $10^{\circ}\text{S}$  to  $10^{\circ}\text{N}$ , balanced by greater descending motion in the subtropics between  $10^{\circ}\text{S}$  and  $30^{\circ}\text{S}$ . Similar trends in the South American Hadley circulation have also been suggested by Chen et al. (2001) and Chen et al. (2002) which point to a greater upward vertical motion and increased vapor flux in the equatorial-convective regions, while the equatorial and subtropical subsidence regions become drier and less cloudy. Several of these studies, however, based their results on trend analyses from reanalysis data and may therefore be affected to some degree by spurious trends due to changes in the reanalysis data assimilation system. There have also been indications of significant changes in the zonally overturning Walker circulation over the tropical Pacific. Vecchi et al. (2006) have shown that the Walker circulation has significantly decreased in the 20<sup>th</sup> century, with an increase in sea level pressure (SLP) in the western and a decrease in the eastern tropical Pacific. This change was attributed to increased anthropogenic greenhouse gas forcing, and leads to a shift in mean conditions toward a more El Niño-like state. Since Andean glaciers have a strong dependence on Pacific sea surface temperatures and ENSO, future changes in tropical Pacific climate need to be carefully observed (Vuille et al., 2008a).

## **2.2. Observed glacier retreat (1900-2011)**

### *2.2.1 Venezuela*

Glaciers in Venezuela only reside on three peaks in the Sierra de Merida: Pico Bolivar (5002 m, see Figure on cover page), Humboldt (4942 m), and Bonpland (4839 m). Combined, the 5 remaining cirque glaciers cover only 1.2 km<sup>2</sup> (Carillo, 2011). The glaciers at these locations have been retreating rapidly over the past 100 years and are no longer in equilibrium with the modern climate. Schubert (1992, 1998) showed that these glaciers have lost more than

95% of their covered area since the mid-19<sup>th</sup> century. It is estimated that they covered approximately 10 km<sup>2</sup> in 1910 and about 3 km<sup>2</sup> in 1952. Of the 10 glaciers mapped in 1952, 4 have completely or almost completely disappeared, 1 has disintegrated into firn patches, and the remaining 5 are substantially smaller.

### *2.2.2. Colombia*

Concern over natural hazards mainly initiated monitoring of glaciers in Colombia. Glaciers, active volcanoes, and earthquakes pose a significant threat (Vuille et al., 2007). The 1985 lahar on Nevado del Ruiz was one of the deadliest ever recorded, with 23,000 deaths and most of Armero, a city of about 25,000, disappearing under a mudflow (Hoyos-Patino, 1998). In June 1994, an avalanche originating in the Nevado del Huila killed at least 15,000 people (Hoyos-Patino, 1998).

Dramatic glacier recession took place in the 20<sup>th</sup> century, mostly from the mid-1980s onward (Vuille et al., 2007). Various studies have come up with different figures for the actual extent of the remaining glaciers in Colombia. Jordan et al. (1989) estimated a total of 246 glaciers on 9 mountains and a total glacierized area of 109 km<sup>2</sup>. This study used field work and aerial photography dating from 1957 to 1978. Hoyos-Patino (1998) used Landsat-MSS images from the early 1970s to measure the extent of the ice and snow areas and reported a total area of 104 km<sup>2</sup>. Thouret et al. (1996) gave a range from 100 to 112 km<sup>2</sup> for the glacierized areas. By 2003, according to Ceballos et al. (2006), glacier termini had retreated to 4700-4900 m a.s.l. and the total glacierized area had decreased to 55.4 km<sup>2</sup>.

Today, six glacierized mountain ranges remain in Colombia: Sierra Nevada de Santa Marta (5775 m a.s.l.), Sierra Nevada del Cocuy (5490 m a.s.l.), Volcán Nevado del Ruiz (5400 m a.s.l.), Volcán Nevado de Santa Isabel (5110 m a.s.l.), Volcán Nevado del Tolima (5280 m a.s.l.), and Volcán Nevado del Huila (5655 m a.s.l.). Eight tropical glaciers disappeared entirely in Colombia during the 20th century (Ceballos et al., 2006).

A study by Poveda and Pineda (2009) aimed to update the estimations made by Ceballos et al. (2006) by using Landsat TM and TM+ imagery for the period 1987-2007. Their study revealed the following:

1. Sierra Nevada de Santa Marta. Estimates of glacierized area are 10.14 km<sup>2</sup> in 1989, 7.33 km<sup>2</sup> in 2002, and 5.95 km<sup>2</sup> in 2007. During the period from 1989-2007, the mountain range lost 41% of its area, with an average retreat rate of 232,611 m<sup>2</sup> yr<sup>-1</sup>, although since the year 2000 this rate has increased to 275,000 m<sup>2</sup> yr<sup>-1</sup>. This glacier is most vulnerable to global warming due to its high spatial fragmentation and geographical and environmental characteristics. Scale and edge effects increase tropical glacier retreat when they reach a critical size (Ceballos et al., 2006; Francou et al., 2003).

2. Sierra Nevada del Cocuy. Estimates of glacierized area are 28.66 km<sup>2</sup> in 1989, 22.9 km<sup>2</sup> in 2000, and 17.00 km<sup>2</sup> in 2007. During the period from 1989-2007, it lost 41% of its glacier area, with an average annual retreat rate of 648,000 m<sup>2</sup> yr<sup>-1</sup>, although since the year 2000 the rate of ice loss has increased to 843,000 m<sup>2</sup> yr<sup>-1</sup>. The glaciers on Sierra Nevada del Cocuy exhibit the largest net retreat rate among the six studied here, including the 2000-2007 period.
3. Nevado del Ruiz volcano. Estimates of glacierized area are 14.06 km<sup>2</sup> in 1989, and 8.66 km<sup>2</sup> in 2004. During the period from 1989-2004, it lost 38% of its glacier area, with an average annual retreat rate of 360,000 m<sup>2</sup> yr<sup>-1</sup>. Nevado del Ruiz currently exhibits low-level volcanic activity, which increases the warming process and glacier loss.
4. Nevado de Santa Isabel volcano. Estimates of glacierized area are 6.50 km<sup>2</sup> in 1989, 5.19 km<sup>2</sup> in 1991, and 3.28 km<sup>2</sup> in 2004. During the period from 1989-2004, it lost 49% of its glacier area, with an average annual retreat rate of 214,000 m<sup>2</sup> yr<sup>-1</sup>. The cause for the glacier retreat is due to climate change as there is no sign of volcanic activity (Euscátegui and Ceballos, 2002).
5. Nevado del Tolima volcano. Estimates of glacierized area are 1.27 km<sup>2</sup> in 1991, and 0.96 km<sup>2</sup> in 2004. During the period from 1991-2004, it lost 24% of its glacier area, with an average annual retreat rate of 24,000 m<sup>2</sup> yr<sup>-1</sup>.
6. Nevado del Huilo volcano. Estimates of glacierized area are 18.39 km<sup>2</sup> in 1989, 13.84 km<sup>2</sup> in 2001, and 7.94 km<sup>2</sup> in 2005. During the period from 1989-2005, it lost 56% of its glacier area, with an average annual retreat rate of 653,000 m<sup>2</sup> yr<sup>-1</sup>. This is the largest areal extent shrinkage of the six glaciers, and since 2006 it has been showing signs of volcanic activity, which may speed up the glacier shrinkage even more.

A summary of the estimated retreat rates from Poveda and Pineda (2009) can be found in Table 1. Their estimates indicated that Colombia's total glacierized area in 2007 amounted to less than 45 km<sup>2</sup>, with an average glacier retreat estimated as roughly 3.0 km<sup>2</sup> yr<sup>-1</sup>. Glacier termini were found to be around 4800 m a.s.l. The likely cause for the glacier retreat rates is the increase in average minimum and mean temperatures. It is less likely that glaciers' retreat have been caused by a decrease in precipitation since no obvious regional or national trends have been found in rainfall records (Poveda and Pineda, 2009).

**Table 1** Summary of Colombia's estimated glacier retreat rates and their remaining areas (from Poveda and Pineda, 2009).

GLACIER	PERIOD	AREA LOSS (%)	MEAN RETREAT RATE (m <sup>2</sup> yr <sup>-1</sup> )	REMAINING AREA (km <sup>2</sup> )
Sierra Nevada de Santa Marta	1989-2007	41	275,000	6
Sierra Nevada del Cocuy	1989-2007	40	843,000	17
Nevado del Ruiz	1989-2004	38	360,000	8
Nevado de Santa Isabel	1989-2004	49	214,000	4
Nevado del Tolima	1991-2004	49	24,000	2
Nevado del Huila	1989-2005	56	653,000	8

### 2.2.3. Ecuador

Ecuador's glaciers are located closer to the equator than any other Andean glaciers and are therefore considered typical examples of continental tropical glaciation (Hastenrath, 1981; Jordan and Hastenrath, 1998). The glaciers, which are mostly located on mountain ranges of volcanic origin, are restricted to the highest peaks and are not made up of large contiguous ice fields, as in Peru and Bolivia. They occur as ice caps that feed many outlet glaciers and are confined to the limited summit areas (Jordan and Hastenrath, 1998).

The glaciers are located on two mountain chains, the Cordillera Occidental and the Cordillera Oriental. According to Jordan and Hastenrath (1998), 4 mountains are glacierized in the Cordillera Occidental and 13 in the Cordillera Oriental. Exposure to the moisture of the Amazon basin allows glaciers to be more common in the Cordillera Oriental. The glacierized area in Ecuador in 1998 totaled 97.21 km<sup>2</sup>, of which 21.92 km<sup>2</sup> was located in the Cordillera Occidental and 75.29 km<sup>2</sup> in the Cordillera Oriental (Jordan and Hastenrath, 1998).

Antizana 15 glacier is located 40 km east of Quito and is of special interest given the use of its glacial runoff for the capital's water supply (Francou et al., 2004). Aerial photogrammetry, which started in 1956, has been used to show a long term perspective beyond the on-site monitoring that began in 1995 (Francou et al., 2000; 2004). Results show that the glacier retreated 7-8 times faster between 1995 and 2000 than during the previous period 1956-1993 (Francou et al., 2000). Strong El Niño events influence this period and a later study (Francou et al., 2004) confirmed the glacier mass balance sensitivity on Antizana 15 to ENSO extremes.

Glacier extent and recession since the mid 1950s was also reconstructed on Cotopaxi volcano using aerial photography (Jordan et al., 2005). The results showed that the glaciers on Cotopaxi were almost stagnant between 1956 and 1976 and then lost approximately 30% of their surface area between 1976 and

1997 and 42% between 1976 and 2006 (Caceres, 2011). The total mass (thickness) loss on selected snouts of Cotopaxi between 1976 and 1997 equals 78 m, or 3-4 m w.e. yr<sup>-1</sup>, which is consistent with similar values obtained from Antizana.

Glacier retreat on Chimborazo volcano was also quite dramatic over the past few decades with glaciers losing 59.3% of their surface area between 1962 and 1997 (Caceres, 2011).

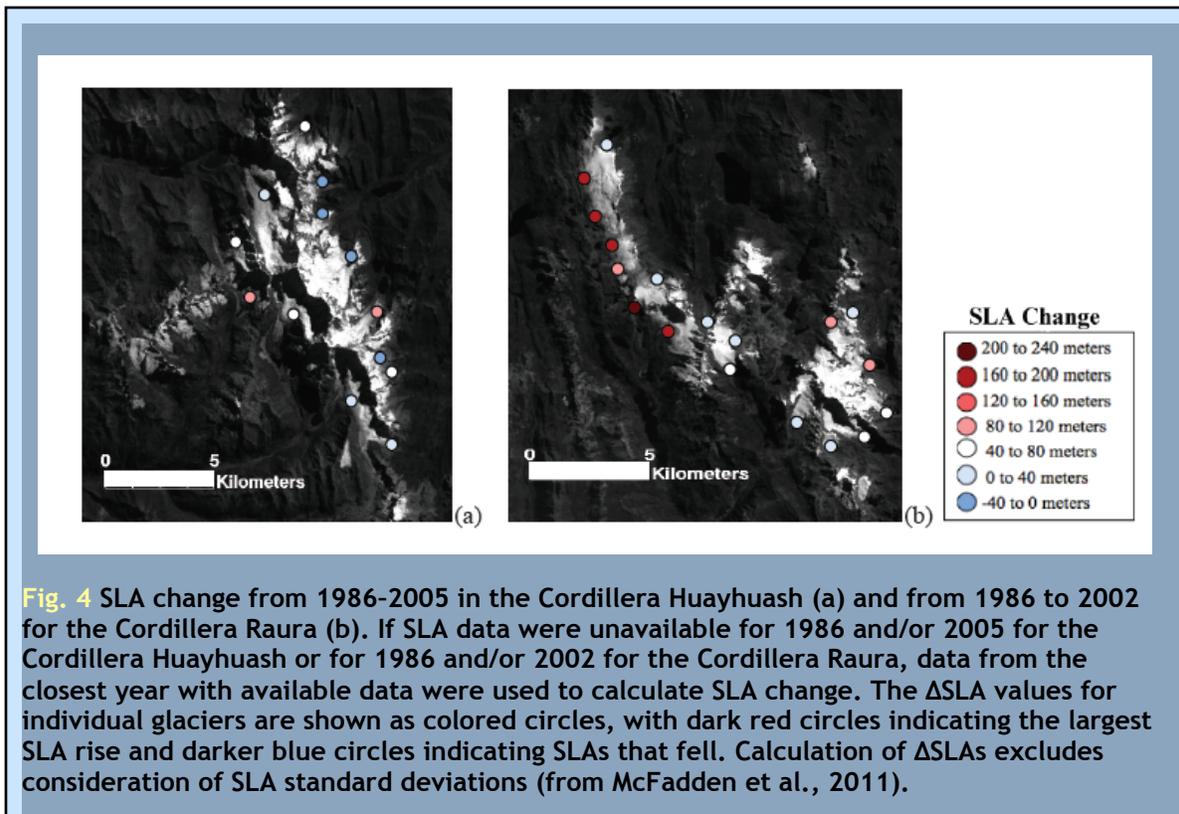
#### *2.2.4. Peru*

The largest fraction of tropical glaciers, and among the most studied, are located in the Peruvian Andes. In 1988, the total ice covered area was estimated at 2,600 km<sup>2</sup> (Morales-Arno, 1998). The Quelccaya Ice Cap is the largest single ice body in Peru and is located in the Cordillera Vilcanota in the eastern branch of the Peruvian Andes. In 1998, its size was estimated at 54 km<sup>2</sup> (Hastenrath, 1998). As shown by Bradley et al. (2009) and discussed in section 2.1.1. the freezing level now frequently extends even beyond the peak elevation of the ice cap at 5680 m. These results coincide with other research revealing a significant recession of the ice cap around its margins (Thompson, 2000; Thompson et al., 2006; Buffen et al., 2009; Hardy and Hardy, 2008). Glaciological observations at the ice cap summit show that the percolation facies (an indicator of surface melting) rose 130 m from 1976-1991 (~8 m yr<sup>-1</sup>) (Thompson et al., 1993).

Eight of the next largest glaciers in Peru are located in the Cordillera Blanca, the world's most extensively glacier-covered tropical mountain range (Morales-Arno, 1998). Based on air photos from 1962 to 1970, a total of 722 glaciers were recognized in the Cordillera Blanca, covering an area of 723.4 km<sup>2</sup> (Ames et al., 1989). Ice cover by the end of the 20<sup>th</sup> century in the Cordillera Blanca has been estimated to be less than 600 km<sup>2</sup> (Georges, 2004). The estimated Equilibrium Line Altitude (ELA) was generally higher for glaciers on the western flanks than on the eastern side due to the east-west precipitation gradient (Mark, 2007). Glaciers in the Cordillera Blanca have been rapidly receding over the past few decades, though there have been brief periods of advancement (Vuille et al., 2008a). Racoviteanu et al. (2008) concluded a 22.4% decrease in the total glacier area between 1970 and 2003, with no significant difference found between glaciers on the eastern and western side of the divide. On Huascaran-Chopicalqui, glacier extent has decreased from 71 km<sup>2</sup> in 1920 to 58 km<sup>2</sup> in 1970 and the ELA rose by ~95 m (Kaser et al., 1996). A tongue retreat of 1140 m on glacier Artesonraju was observed between 1932 and 1987 (Ames, 1998), while the glacier surface area decreased by 20% between 1962 and 2003 (Raup et al., 2006). Glacier Broggi's terminus retreated 1079 m between 1932 and 1994, even with a slight advance around 1977 (Ames, 1998). Glacier Pucaranra and glacier Uruashraju decreased in length by 690 m and 675 m respectively between 1936 and 1994 (Ames, 1998). Glacier Yanamarey is one of the most studied sites of glacier hydrology

in the Peruvian Cordillera Blanca (Bury et al., 2011). Between 1948 and 1988, glacier Yanamarey experienced a tongue retreat of 350 m (Hastenrath and Ames, 1995a) and 552 m between 1932 and 1994 (Ames, 1998). Since 1948, the terminus has receded over 800 m (Bury et al., 2011; Vuille et al., 2008a). The average rate of retreat between 1977 and 2003 was estimated at  $20 \text{ m yr}^{-1}$ , which was four times the rate observed between 1948 and 1977 (Mark et al., 2005). After 1970, the average decadal recession rates show an acceleration of  $8 \text{ m decade}^{-2}$ . The average rate over the past 6 years also shows an increase at greater than  $30 \text{ m yr}^{-1}$  (Bury et al., 2011). Glacier recession in this area has consequently led to a decrease in ice volume. From 1948 to 1982 volume loss on Yanamarey was estimated at  $22 \times 10^6 \text{ m}^3$ , with an additional loss of  $7 \times 10^6 \text{ m}^3$  between 1982 and 1988 (Hastenrath and Ames, 1995a).

In addition to the heavily studied glaciers in the Cordillera Blanca, research has also focused on other mountain ranges. Coropuna is a glacierized volcano located in the Cordillera Ampato in southwestern Peru. Racoviteanu et al. (2007) found a significant decrease in the glacier extent from  $82.6 \text{ km}^2$  in 1962 to  $60.8 \text{ km}^2$  in 2000. They also found changes in the thickness of the glacier, with a thickening in the summit region and a thinning at lower elevations. McFadden et al. (2011) studied changes in mean snowline altitudes (SLA) for the Cordillera Huayhuash and the Cordillera Raura (Fig. 4).



Their results indicate a significant rise in mean SLA in the Cordillera Raura from  $4947 \pm 7 \text{ m a.s.l.}$  to  $5044 \pm 8 \text{ m a.s.l.}$  from 1986 to 2002, while mean SLA rise in the Cordillera Huayhuash was statistically insignificant at  $5062$

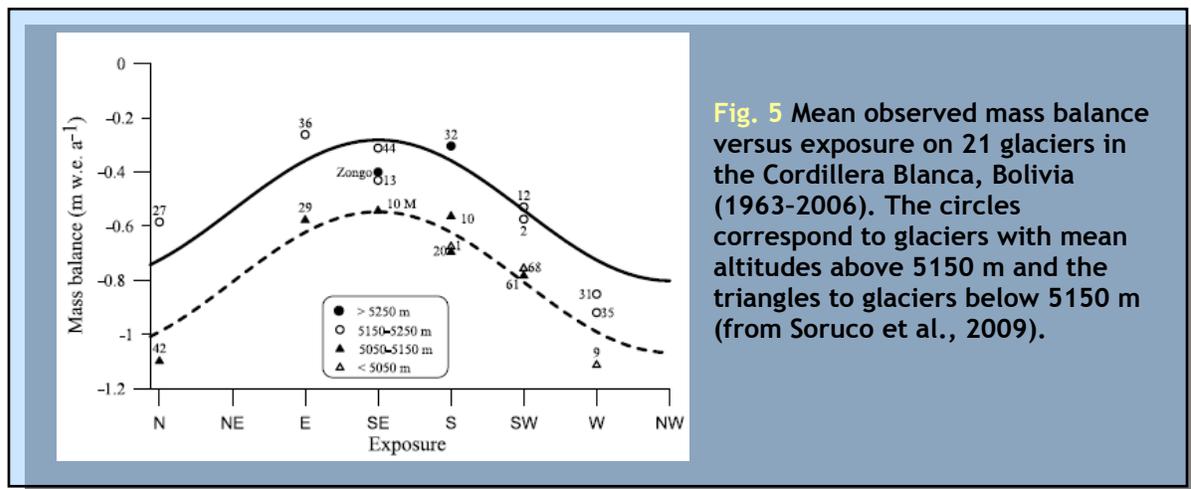
$\pm 36$  m a.s.l. to  $5086 \pm 35$  m a.s.l. from 1986 to 2005. The eastern SLA of both ranges rose at a slower rate than their respective western SLA, likely caused by a combination of factors such as changes in humidity, precipitation, and cloud cover rather than a temperature change alone (McFadden et al., 2011; Kaser and Georges, 1997).

### *2.2.5. Bolivia*

Glaciers in Bolivia are found on two main mountain ranges, the Cordillera Occidental and the Cordillera Oriental, which is further separated into the Cordilleras Apolobamba, Real, Tres Cruces and Nevado Santa Vera Cruz. Glaciers in the Cordillera Occidental are limited to Nevado Sajama and its nearby volcanoes (Vuille et al., 2008a). These small ice caps are exposed to dry conditions and result in the highest minimum elevations on earth, with an ELA several hundred meters above the  $0^{\circ}\text{C}$  isotherm (Messerli et al., 1993; Arnaud et al., 2001). The eastern Cordilleras house most of the glaciers and consist of ice caps, valley and mountain glaciers. Due to limited precipitation, no glaciers exist today in southern Bolivia (Messerli et al., 1993).

Rapid glacier retreat has been observed in the 20<sup>th</sup> century, especially since the 1980s (Jomelli et al., 2009, 2011). Glaciers on Charquini in the Cordillera Real have lost between 65 and 78% of their Little Ice Age (LIA) size and the ELA rose by approximately 160 m from  $\sim 4900$  m during the LIA maximum extent to  $\sim 5060$  m in 1997. 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.  $\text{yr}^{-1}$  between 1983 and 1997 (Rabatel et al., 2006). Chacaltaya glacier was also located in the Cordillera Real and used to serve as a small ski resort (the world's highest at 5400 m) for the urban population of La Paz. Between 1940 when its size was  $0.22$   $\text{km}^2$  and 1983 the glacier lost 62% of its mass. In 1998 its remaining size was only  $0.01$   $\text{km}^2$  or 7% of the extent in 1940 (Francou et al., 2000). 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. $\text{yr}^{-1}$  and it 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). By 2009 the glacier had completely disappeared (see Figure on cover page). Chacaltaya is representative of many of the glaciers in the region, since more than 80% of all glaciers in the Cordillera Real are less than  $0.5$   $\text{km}^2$  in size (Francou et al., 2000). Chacaltaya is also a clear example of how glacier retreat accelerates once a glacier reaches a critical size where edge effects of warm air advection from the surrounding rocks become critically important (Francou et al., 2003). Similar results have been reported from the nearby Tuni- Condoriri massif, where glaciers have lost between 49 and 62% of their surface area between 1956 and 2009 (Ramirez, 2011). Soruco et al., (2009) reported mass balance changes on 21 glaciers in the Cordillera Real between 1963 and 2006 and were able to express the average mass balance of the glaciers as a function of their exposure and altitude. Using this relationship an assessment was made of 376

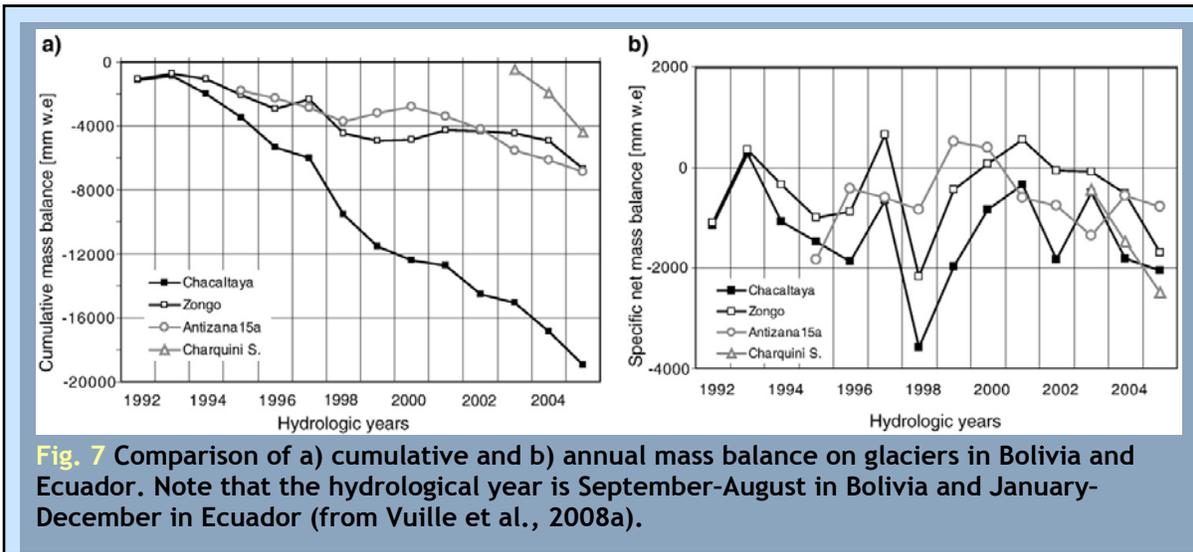
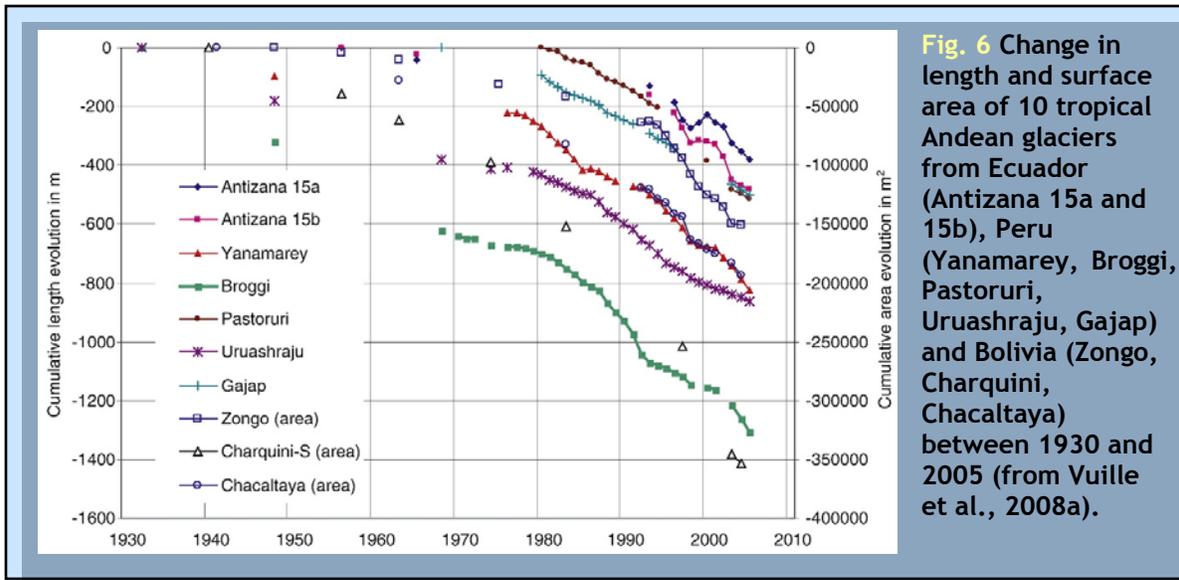
glaciers in the region, resulting in an estimated 43% (0.9 km<sup>3</sup>) volume loss between 1963 and 2006 and a 48% decline in surface area between 1975 and 2006. Figure 5 shows the mean glacier mass balance variation as a function of exposure and altitude. Glaciers at the highest elevation and those exposed to the east and south have a less negative mass balance. The more negative mass balance on glaciers with western exposure can be explained by accumulation differences between the eastern and western exposures, considering that most of the precipitation comes from the east. Mean solar incident radiation is higher for northern exposure most of the year due to the tropical location of these glaciers (Soruco et al., 2009).



### 2.2.6. Summary

As shown in the previous sections glaciers are retreating in every country of the tropical Andes. A summary of length and surface area changes of 10 Andean glaciers from Ecuador, Peru, and Bolivia between 1930 and 2005 is shown in Figure 6 and highlights the acceleration in the retreat that can be observed since the 1990s.

The retreat is the result of a generally negative mass balance of glaciers, with mass loss (melt and sublimation) outpacing mass gain through snowfall. Mass balance records, where available, show similar results throughout the tropical Andes, with a generally negative mass balance (Fig. 7). Occasional periods of equilibrated or positive mass balance often coincide with La Niña events, which are associated with cool and wet conditions in the tropical Andes (Vuille et al., 2000a, Vuille et al., 2000b, Vuille et al., 2008b).



### 3. Impacts of Climate Change

Given the indications of climate change outlined earlier and the impacts already being felt on glaciers in the Cordillera, future changes are sure to exacerbate the effects. Many people living in the Cordillera are dependent on the water supplied by glacial runoff into streams. Additionally, increased temperatures are likely to impact biodiversity as animals and plant species may be forced to adapt or displace and face increasing competition from invasive species and exposure to formerly non-existing diseases. The following section will highlight some of the individual problems brought forth by climate change in the Andes, with an emphasis on problems caused by receding glaciers.

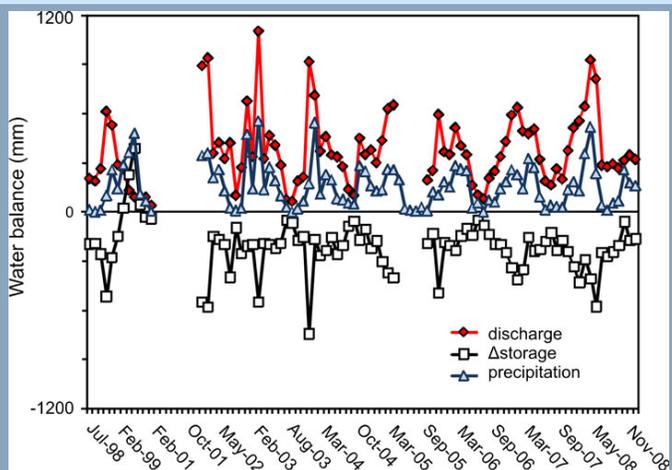
#### 3.1. Impact on water supply

Changes in glacier mass balance as discussed in the previous section have led to significant changes in the seasonal glacier hydrology. Simple budget modeling which assumes that the total volume of water discharging from the catchment is equal to the volume of water entering the catchment plus a change in storage can be used to isolate the glacial melt water contribution to stream discharge as the change in the glacial storage term ( $\Delta\text{storage}$ ):

$$\Delta\text{storage} = \text{precipitation} - \text{discharge}$$

Figure 8 shows that the mass balance of Yanamarey Glacier (YAN) in the Cordillera Blanca is no longer positive, with a constantly negative storage term indicating that that discharge from the catchment is constantly larger than the precipitation input (Bury et al., 2011). Average storage changes in 1998-1999 indicated that glacier melt from Yanamarey contributed  $35 \pm 10\%$  of the annual discharge (Mark and Seltzer, 2003).

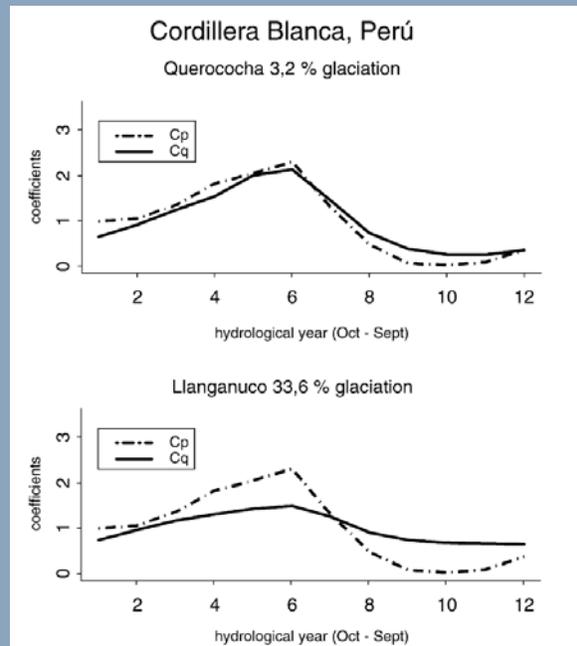
**Fig. 8** Monthly hydrologic mass balance at glacier Yanamarey (Cordillera Blanca, Peru), showing constant release of glacier storage (negative  $\Delta\text{storage}$ ) since 2002, as well as higher peak discharge more coincident with maximum precipitation. All terms in (millimeters) as normalized for the glacier watershed surface area of  $1.35 \text{ km}^2$  (from Bury et al., 2011).



The depletion of water resources from tropical Andean glaciers will increase the variability in streamflow, by reducing the buffer during the dry season. This reduction will affect the availability of drinking water, water for hydropower production, mining and irrigation (e.g. Barry and Seimon, 2000; Barnett et al., 2005; Coudrain et al., 2005; Francou and Coudrain, 2005; Bradley et al., 2006; Diaz et al., 2006; Vuille, 2006).

Kaser et al. (2003) showed that the percentage of glaciated area of tropical Andean catchments is highly correlated with their capacity to store precipitation. An illustrative example is shown in Figure 9 which compares the seasonal cycle of runoff and precipitation from two glaciated catchments in the Cordillera Blanca, Peru. While a third of the Llanganuco catchment is covered by a glacier, the glaciation in the nearby catchment of Querococha is an order of magnitude less. The seasonal cycle of runoff is therefore almost identical to the precipitation seasonal cycle in Querococha as the glacier is not large enough to sufficiently regulate runoff and act as a seasonal storage. In the Llanganuco catchment on the other hand the runoff is much subdued during the wet season, but a significant baseflow is maintained during the dry season despite the absence of significant amounts of precipitation, as the glacier can provide for constant release of meltwater. In a future scenario, where glaciers continue to recede one can assume that the runoff behavior from glaciated catchments will gradually transition from a situation displayed in Llanganuco to a situation characteristic of Querococha, with most of the runoff concentrated in the wet season, and little to no baseflow maintained during the dry season.

**Fig. 9** Seasonal cycle of precipitation ( $C_p$ ) and runoff ( $C_q$ ) in two glaciated catchments and from the Cordillera Blanca, Peru, with different degrees of glaciation (from Kaser et al., 2003).



While glaciers retreat and lose mass they may add to a temporary increase in streamflow due to the rapid melting of the glaciers (Mark et al., 2005; Mark and McKenzie, 2007). This increase however, will not last very long

as the storage term rapidly decreases. It is therefore important to implement adaptation strategies that take into account the long-term changes in seasonally available water resources rather than to adapt to a short term water surplus than is not sustainable into the future.

In the Cordillera Real, Bolivia, studies portray a very similar situation. Research carried out on Zongo glacier, where proglacial runoff has been monitored since the early 1990s and earlier gauge readings by an electric power plant go back to 1973 (Ribstein et al. 1995; Francou et al., 1995; Caballero et al., 2004), indicates that runoff from the catchment is higher than precipitation in the catchment itself. This is consistent with the results from the Cordillera Blanca discussed earlier and confirms that the ice wastage is a larger-scale phenomenon. On Zongo glacier measurements suggest that there was an annual mass deficit of 410 mm per year between 1973 and 1993 (on average 1062 mm precipitation fell in the catchment but 1472 mm were lost due to runoff, with the difference being provided by glacier melt (Ribstein et al., 1995)). Since sublimation was not accounted for in this study, which would have increased the deficit even further, this estimate is likely on the conservative side.

The change in water supply is a problem that many local communities in the Andes are already observing today and they are adapting in a number of ways. Farmers in the town of Catac, Cordillera Blanca, Peru, for example have noticed decreased water supplies during the dry season, and warmer days that are drying out their grasslands and crops (Bury et al., 2011). Their livestock have been affected by decreased streamflow that negatively impacts pasture health and grass productivity. Also since some streams have begun to disappear, animals are now forced into greater daily vertical movement in order to access sufficient water. As a result, herding intensity has increased and livestock growth rates have been negatively affected. Overall, 91% of respondents indicated that they were deeply preoccupied by recent climate change taking place in the region. The main concerns mentioned by interviewees were the impacts of climate change on family and livestock health, agricultural productivity, water availability, and declining fish stocks (Bury et al., 2011). In some areas of Bolivia the warmer temperatures have also lead to a rise in the upper limit of cultivable land (Ramirez, 2011). Hence the changing climate leads to the paradox situation that more land can be cultivated all year long, requiring even more water.

### **3.2. Impact on water quality**

Decreased streamflow has already increased tension between water users in several communities, in particular between local peasants and mining companies. Concerns over safe access to clean water are especially apparent in Peru, which is considered South America's most water-stressed country. Estimates are that mining uses only about 5% of Peru's water; however, mining concessions are located in headwater areas in the high Andes, which increase

the significance of their water use. Also, mining can adversely affect water quality over large distances primarily from acid mine drainage and the escape of ancillary products in processes of production and transformation (Bebbington and Williams, 2008).

Glacier retreat can also directly affect water quality without any additional anthropogenic influence. Recent work by Fortner et al. (2011) found that receding glaciers in the Cordillera Blanca induced sulfide weathering from newly exposed minerals and rocks which has had profound effects on the water quality in the Rio Quilcay. As a result, several water quality parameters in this region have exceeded World Health Organization (WHO), United States Environmental Protection Agency (USEPA), and Peruvian drinking water standards, and recommendations for irrigation and agriculture. Concern has been focused on the levels of Pb, Ni, Al, Fe, Mn, Zn, Co, and pH in the Rio Quilcay. High levels of Pb can affect physical and mental development (USEPA, 2009). Among laboratory animals, elevated doses of Ni can cause kidney failure, lower body mass, and higher newborn deaths. Humans exposed to these levels of Ni may experience headaches, weakness, and digestive complications (WHO, 2006). High concentrations of Fe and Mn have been found to stain clothing and other materials they touch (USEPA, 2009). Elevated Mn in the blood has been linked to neurological problems (Ljung and Vahter, 2007), while high levels of Co is toxic to minnows (Diamond et al., 1992).

### **3.3. Impact on biodiversity**

The composition and abundance of biodiversity can also be affected by glacier retreat and associated changes in runoff. This is primarily the case for wetlands (bofedales), where a number of plant species rely directly on the glacier melt water and its seasonal distribution. Of course the changes in climate, such as increasing temperatures or changes in precipitation (both amount and seasonal distribution) will provide additional stress to species that are trying to cope with changing hydrologic conditions (Holt, 1990; Peterson et al., 2001). The observed upslope movement of the tree line along the eastern slope of the Andes forest on the other hand is an example where certain vegetation zone may be able to expand their habitat, but at the same time encroaching on others. If plant species from the high Andean forest are indeed able to migrate onto expansive areas above the current tree line, their population sizes may increase (Feeley et al., 2011). However, the projected rate of temperature change along the Andean slope is so high (4-5°C in the next 100 yrs, Urrutia and Vuille, 2009) that few species are expected to be able to migrate upslope at a pace that allows them to keep up with the rapid warming (Feeley et al., 2011).

Glacier retreat in the Peruvian Andes has also lead to an increase in the elevational limit of Anurans (frogs and toads). Three species have been found living in formerly glaciated areas at record elevations of up to 5400m above sea level (Seimon et al., 2007). In parallel with the upward extension of their

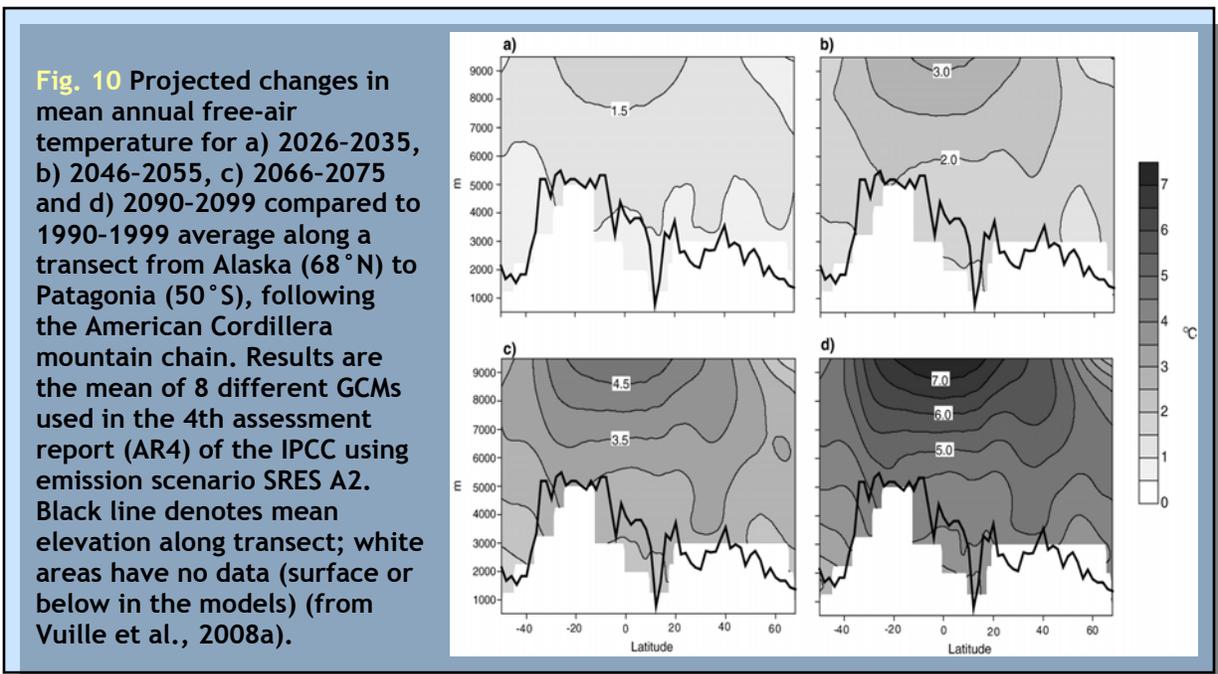
habitat fungal pathogens associated with global amphibian declines have also spread to similar record elevations. This highlights the dangers of future climate change and deglaciation for Andean biodiversity, as they will likely lead to further spread of disease and invasive species.

## 4. Projections for the 21<sup>st</sup> Century

Changes in temperature, precipitation and streamflow are three of the main parameters that will affect environmental services, biodiversity and socioeconomic activity in the tropical Andes in the 21<sup>st</sup> century. Here we review the main projections for these three variables based on model simulations of varying resolution and complexity.

### 4.1. Temperature projections

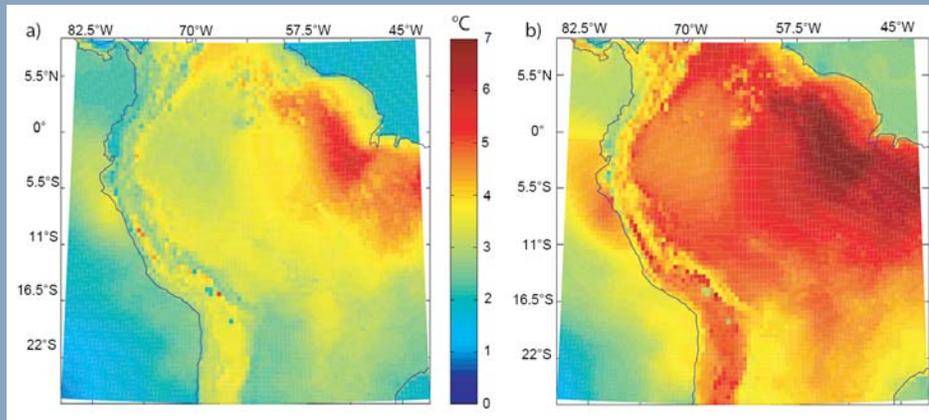
Bradley et al. (2004) analyzed free tropospheric temperature changes in the American Cordillera based on simulations from seven different General Circulation Models (GCMs) with doubled CO<sub>2</sub> concentrations. Temperature changes were large and increased with elevation compared with control runs. In the tropical Andes, the projected temperature changes were on the order of 2.5-3°C year-round. In a subsequent analysis Bradley et al. (2006) analyzed changes to annual free-air temperature based on eight different GCMs for the end of the 21<sup>st</sup> century along the same transect from Alaska to Patagonia using CO<sub>2</sub> concentrations from the high-emission IPCC-scenario SRES A2 (Nakicenovic and Swart, 2000). Following this SRES A2 emission scenario, the tropical Andes will experience a significant warming on the order of 4.5-5°C by the end of the 21<sup>st</sup> century, with larger temperature increases at higher elevations (Fig. 10).



An analysis by Boulanger et al. (2006) focused on changes in surface rather than free tropospheric temperature. According to their study, tropical South America is likely to warm more (by 3-4°C in the SRES A2 scenario) than the southern part of the continent. They were also able to show that using

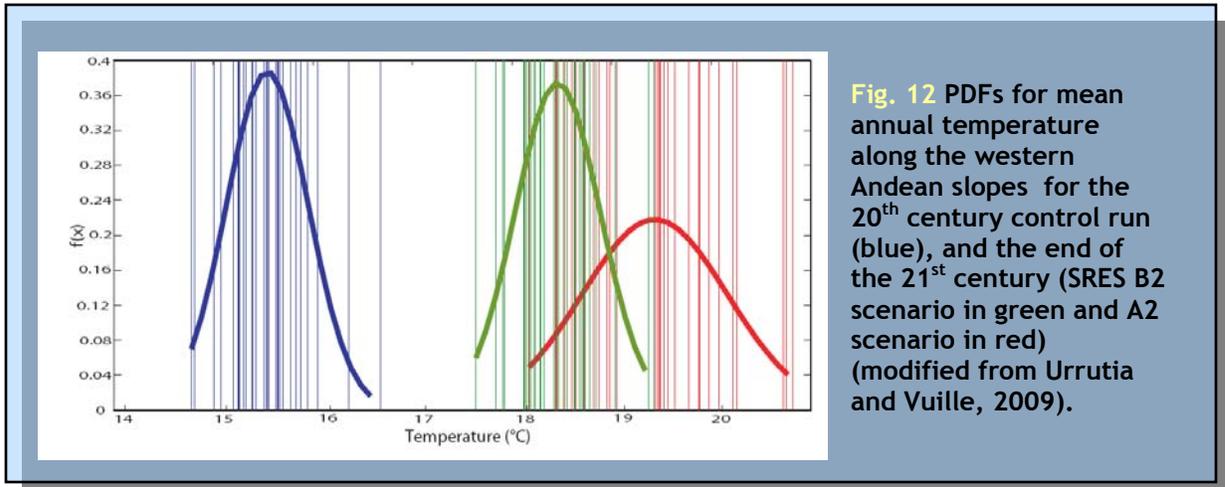
different scenarios (SRES A1B, A2 and B1) greatly changed their results. SRES A1B reaches about 80-90% of the warming in the SRES A2 scenario at the end of the century, while the more moderate and optimistic path SRES B1 path shows only about half the warming of SRES A2.

Urrutia and Vuille (2009) conducted the first study looking at projected temperature trends for the Andes at the end of the 21<sup>st</sup> century using a high-resolution, regional climate model. The use of a regional climate model is an important step forward in analyzing climate trends over the mountain range as GCMs are far too coarse to accurately simulate changes in surface climate over a region with such a complex topography and steep climatic gradients. Figure 11 shows the projected future warming of mean annual surface temperature by the end of the 21<sup>st</sup> century based on two different emission scenarios, a high emission scenario, A2 and a low emission scenario B2. Projected changes in temperature along the Andes indicate substantial warming of 5-6 °C in many parts of the Andes in the A2 scenario, with the largest warming occurring at high elevations in the Cordillera Blanca region, Peru. In the lower emission B2 pattern the surface warming is only half the amplitude of A2, but the spatial pattern of the observed warming is very similar.



**Fig. 11** (a) Difference in mean annual surface temperature (in °C) between the SRES B2 scenario (2071-2100) and the 20<sup>th</sup> century control run (1961-90). (b) Same as in (a) but for SRES A2 (from Urrutia and Vuille, 2009).

Probability density functions (PDF) indicate that Andean temperature by 2071-2100 will be significantly warmer, exhibit a much larger interannual variability, a higher likelihood of extremely hot years and that even the coldest years in an A2 or B2 scenario are much warmer than the warmest years observed today (Urrutia and Vuille, Fig. 12). Such non-analog climates will cause the assemblage of novel vegetation types and ecosystems and may lead to extinction of many species that are unable to adapt to completely new climates over such a short time frame.



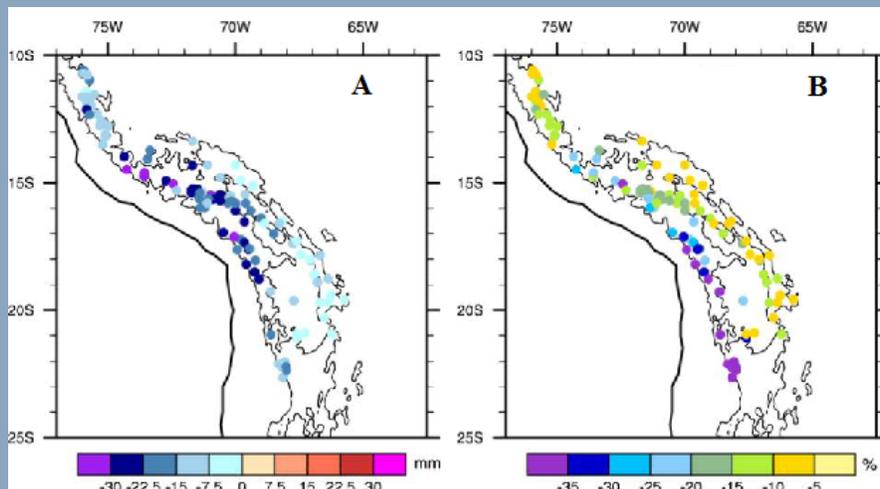
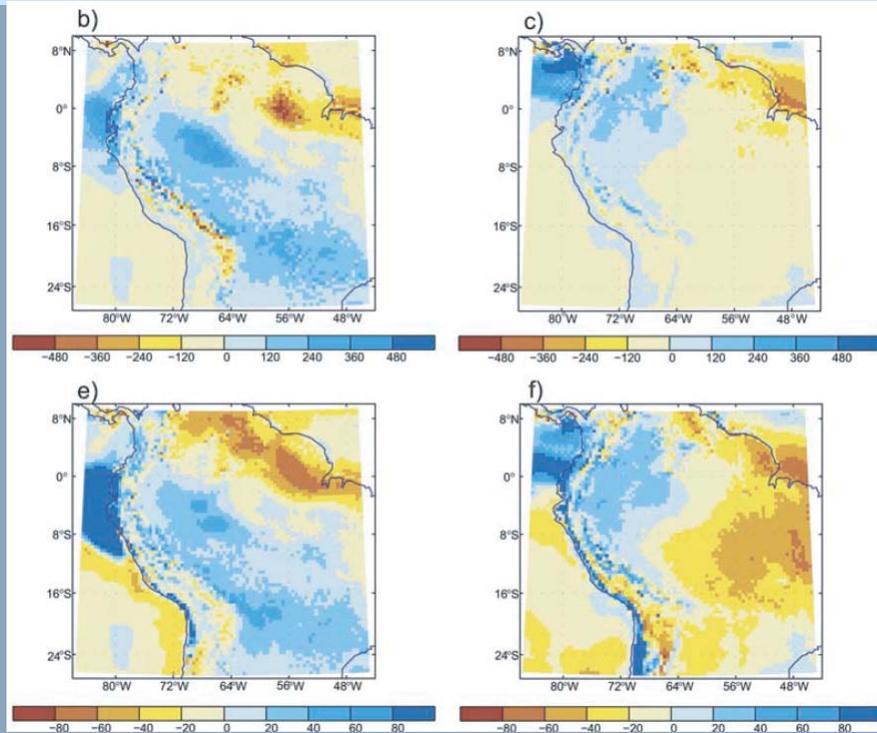
## 4.2. Precipitation projections

Regional precipitation is more difficult to estimate, partly because of the low-resolution of current GCMs relative to the cross-mountain scale of the Andes (Minvielle and Garreaud, 2011). Vera et al. (2006) looked at changes in South America using the models from the IPCC-AR4. They analyzed the change in precipitation in the SRES A1B scenario during the period 2070-2099, compared with the control period 1970-1999. Most models predict an increase in precipitation during the wet season and a decrease during the dry season in the tropical Andes. This result was also obtained by Seth et al. (2010) in their analysis of precipitation changes over the Altiplano region using nine CMIP3 global coupled climate models, initiated with the SRES A2 scenario. Urrutia and Vuille (2009) examined precipitation trends in the Andes by the end of the century following a high-emission A2 scenario using a regional climate model. Their results (Fig. 13) suggest a future increase in precipitation along the coastal regions of Colombia and Ecuador and in some places along the eastern Andes south of the equator, while the southern tropical Andes, including the Altiplano regions, according to their results, will likely experience increased drought in the future.

Minvielle and Garreaud (2011) used 11 CMIP3 GCMs initiated at the SRES A2 scenario to investigate precipitation changes on the Altiplano. Since the current generation of GCMs provide a rather inconsistent picture of future changes in precipitation over regions of complex terrain, but models are generally able to accurately simulate changes in the large scale atmospheric circulation, the observed very close empirical relationship between 200 hPa level zonal winds and precipitation over the central Andes was exploited to project changes in regional rainfall for the end of the 21<sup>st</sup> century. An examination of the projected change in the free-tropospheric wind field indicated an almost year-round increase in westerly flow at middle and upper-levels over the central Andes. Enhanced westerlies result in a decrease of the

moisture transport toward the Altiplano from the interior of the continent during summer, possibly reducing the summer precipitation by the end of the century between 10-30% relative to current values (Fig. 14).

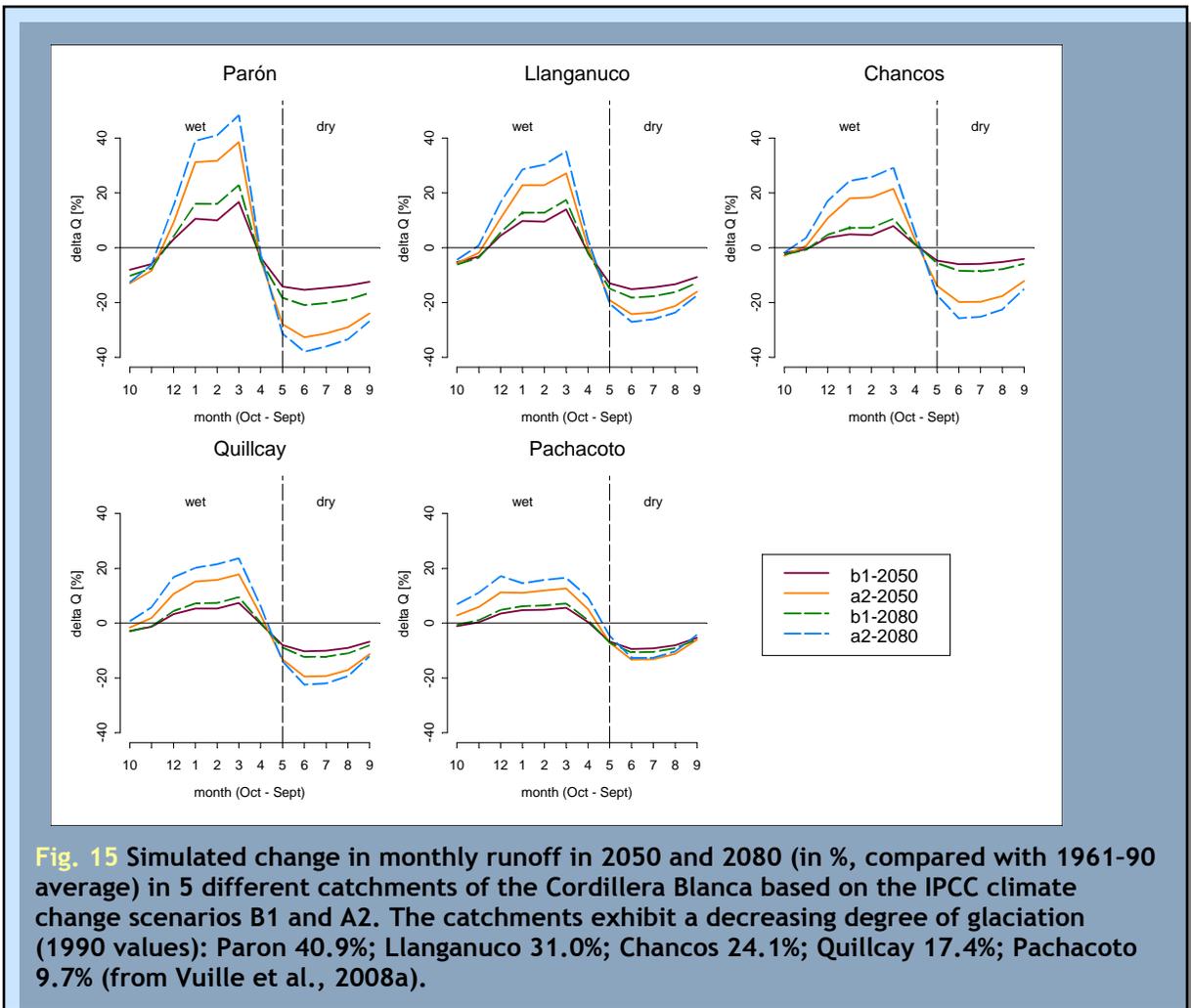
**Fig. 13** Absolute difference in (b) DJF and (c) JJA precipitation totals (in millimeters) between regional climate model simulations using the SRES A2 (2071-2100) scenario and a 20<sup>th</sup> century (1961-1990) control run. (e and f) Same as (b and c) but for relative difference (in percent) (modified from Urrutia and Vuille, 2009).



**Fig. 14** (a) DJF rainfall change (in mm/month) between the 2070-2099 A2 scenario and a 1970-1999 control run in the Altiplano region, estimated based on projected changes in the upper-air wind field. (b) Same as (a) but for relative precipitation changes (in %). Thin black line indicates the 4000 m topographic contour (modified from Minvielle and Garreaud, 2011).

### 4.3. Projected changes in streamflow

It is clear that climatic changes under way will have a substantial effect on Andean glaciers and associated glacial runoff and streamflow. Changes in river runoff are generally expected to be largest in regions such as Peru, where rivers enter seasonally arid regions (Kaser et al., 2010). Figure 15 highlights one case study from selected catchments in the Cordillera Blanca, Peru, demonstrating how monthly runoff might change based on simulations of streamflow out to the years 2050 and 2080 using a low (SRES B1) and high (A2) emission scenario (Juen et al., 2007).



These results are based on simulations using a glacier-runoff model, specifically designed for climatic conditions as they prevail on tropical glaciers. The model was fed with output from several GCMs, for these specific time periods and emission scenarios. As shown in Figure 15 dry season runoff is significantly reduced, particularly in the A2 scenario, while wet season discharge is higher due to the larger glacier-free areas and enhanced direct

runoff. Indeed the overall discharge does not change very much, but the seasonality intensifies significantly. Changes in streamflow are far greater in 2050 in the A2 scenario than in 2080 under the more moderate B1 scenario, illustrating a strong dependency on the emission path and the need for considering multiple scenarios. The difference in the amplitude of the simulated streamflow change between the five catchments is primarily a reflection of the current degree of glaciation within the catchments. The relative glacier covered area decreases from the top left (Paron, heavily glaciated) toward the lower right (Pachacoto, barely glaciated). Hence a currently heavily glaciated catchment such as Paron is projected to undergo a large change in its seasonal runoff behavior as glaciers become smaller and smaller in the future. A catchment such as Pachacoto on the other hand, where the glacier is already small and unable to provide for a substantial seasonal buffering of runoff today, the change will not be very large, regardless of whether the glacier disappears entirely in the future. These results clearly highlight the importance of considering future changes and hence any adaptation measures on a case by case basis, rather than implementing broad brush measures which may not be adequate for many watersheds.

Other studies have come to slightly different conclusions. Pouyaud et al. (2005) for example simulated runoff in several catchments of the Cordillera Blanca out to the year 2300 by applying a uniform, but unrealistically low, linear warming rate of only  $\sim 1^{\circ}\text{C}$  per century. In their simulations runoff continues to increase for another 25-50 years before it starts to decrease around the middle of the century.

## **5. Adaptation strategies**

This paper has provided an update on the current knowledge of climate change and its impacts on tropical Andean glaciers and their hydrology. It is clear that adaptation strategies should be implemented without delay in order to mitigate these effects, yet at the same time the scientific knowledge is not really sufficiently advanced to adequately guide such implementations. Below we outline a few avenues where scientific or policy instruments could help improve this situation and provide guidance for technological adaptation.

### **5.1. Technological adaptation**

A number of measures to alleviate water-stress could be quite easily introduced if the political and economic circumstances were improved. For example water conservation measures such as shifts toward less water-intensive agriculture could help reduce the water demand in many regions. Similarly the construction of new water treatments plants would reduce the waste of highly polluted water that goes unused. In other cases such measures may prove insufficient and new water resources may have to be exploited, if available (Vergara, 2005). In other instances creation of water reservoirs may help as dams can essentially provide the same environmental function as glaciers, although building of such reservoirs comes along with loss of land and potentially the displacement of local populations. In addition the lifetime of dams is often affected by high sedimentation rates due to large suspended sediment loads in glacial riverbeds.

### **5.2. Scientific strategies and policy instruments**

It is important to realize that many aspects of future climate change in the region remain highly uncertain, primarily due to limitations imposed by an old and inadequate climatic and glaciologic monitoring network in the region (Francou et al., 2005; Coudrain et al., 2005; Kaser et al., 2005; Casassa et al., 2007). A network of automated weather stations at high elevations is needed to monitor climate change at the elevation of the glacier, where the changes are the most dramatic (Bradley et al., 2004, 2006). Improved stream discharge gauging is needed to quantify the net hydrologic yield of glacierized watersheds (Mark and Seltzer, 2005b). In addition to needed improvements in on-site monitoring, a better inclusion of these data with advanced remote sensing and GIS applications is desperately needed (Vuille et al., 2007c). SRTM data, GPS and satellite data such as Landsat, ASTER and SPOT now offer a wealth of opportunities to provide a much more detailed picture of ongoing changes in the Andean cryosphere. They should, of course, not be viewed as a substitute for on-site measurements, but they can provide a much needed complementary picture (Vuille et al., 2008a). On the modeling front, more

detailed climate change projections, relying on a variety of models and several different emissions scenarios are needed. Large uncertainties still exist in the current generation of climate and hydrologic models (e.g. Buytaert, et al., 2010) and statistical and dynamical downscaling of global climate projections to the Andean region is still in its infancy. High-resolution regional climate models, coupled with tropical glacier-mass balance models will help in assessing the implications for glacier mass balance and water resources at a catchment-scale level (Vuille et al., 2008a).

Finally, greater collaboration between agencies and institutions needs to take place and include exchanges with local scientists, stakeholders, and decision makers (Mark and Seltzer, 2005b). In particular scientific results need to be made accessible and translated into a language that is understandable by and applicable to stakeholders and water users (Viviroli et al., 2011). This will require much closer collaboration between scientists, water managers and local populations but also enhanced capacity building through training and education programs. Much of this could be achieved in collaboration with local partner agencies in the affected countries. Close collaboration with scientists abroad could include exchange of scientific expertise, for example through summer schools, fellowships, and through training and education of South American students at partner institutions in the U.S. and Europe. In the end only the combination of various approaches will allow us to achieve the ultimate goal, which is to reduce the vulnerability and increase the resilience of water users affected by tropical glacier retreat. Because of the scale and complexity of this problem, the review provided in this document should merely be considered as a first step in an on-going process to obtain a better understanding regarding climate change and its impacts on the glaciological and hydrological systems in the Andes.

## 6. References

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