Available online at www.sciencedirect.com

ScienceDirect

Global and Planetary Change 62 (2008) 14–28

GLOBAL AND PLANETARY CHANGE

www.elsevier.com/locate/gloplacha

Glacier mass balance variability in the Cordillera Blanca, Peru and its relationship with climate and the large-scale circulation

Mathias Vuille [a],*, Georg Kaser [b], Irmgard Juen [b]

[a] Climate System Research Center, Department of Geosciences, University of Massachusetts, Morrill Science Center, 611 North Pleasant Street, Amherst, MA 01003-9297, USA

[b] Tropical Glaciology Group, Institute of Geography, University of Innsbruck, Austria

Received 10 August 2007; accepted 15 November 2007
Available online 23 November 2007

Abstract

A 41-year-long reconstructed annual mean glacier mass balance record from the Cordillera Blanca, Peru, was investigated for its climate sensitivity toward temperature, humidity and precipitation, and its links with the large-scale atmospheric circulation. On interannual timescales precipitation variability appears to be the main driver for glacier mass balance fluctuations in the Cordillera Blanca. This is corroborated by an analysis of the relationship between mass balance variations and local- to regional-scale precipitation variability. Temperature tends to enhance precipitation in driving the mass balance signal, as dry years are often characterized by warm conditions, while wet years usually coincide with cold anomalies. In some years, however, warm and wet or cold and dry conditions coincide, under which circumstances temperature minimizes or even neutralizes the effects of precipitation. Surface energy balance studies have shown that changes in atmospheric humidity significantly affect the melt rates of tropical glaciers, but the lack of long and high-quality in-situ measurements precludes a detailed quantitative assessment of its role on interannual timescales in the Cordillera Blanca. Sea surface temperature anomalies (SSTA) in the tropical Pacific exert the dominant large-scale forcing on interannual time scales, leading to negative mass balance anomalies during El Niño and above average mass balance during La Niña episodes. In general the teleconnection mechanism linking ENSO with glacier mass balance is similar to what has previously been described for the Bolivian Altiplano region. Changes in the upper-tropospheric zonal flow aloft associated with ENSO conditions determine the amount of snowfall during the wet season and thereby significantly affect the glacier mass balance. Because this teleconnection mechanism is spatially unstable and oscillates latitudinally along the subtropical Andes, it affects the Cordillera Blanca in most, but not all years. The relationship between ENSO and glacier mass balance is therefore characterized by occasional 'break downs', more common since the mid-1970's, when El Niño years with above average mass balance and La Niña events with negative mass balance have been observed.

Keywords: Andes; glaciers; climate change; ENSO

---

1. Introduction

Glaciers in the Andes of Peru provide an important environmental and economic service by releasing meltwater for the arid western part of the country during the dry season, May–September, when little to no rainfall occurs. Much of the water resources consumed for agricultural, domestic and industrial purposes on the arid west coast of Peru originate from snow and ice in the high Andes. The glaciers effectively buffer the runoff by storing much of the precipitation falling as snow on the glaciers during the wet season, October–April, and releasing it throughout the year, including during the dry season when it is most needed. This regulating role of the glaciers is even more pronounced in the tropics than in mid-latitudes, because the lack of thermal seasons precludes the build-up of a seasonal (winter) snow cover outside of the glaciated areas. Hence the contribution of seasonal snow melt to runoff, important in places such as the Alps or the Rockies during the

---

* Corresponding author. Present address: Department of Earth and Atmospheric Sciences, University at Albany, State University of New York, 1400 Washington Avenue, Albany, NY 2222, USA. Tel.: +1 413 545 0229; fax: +1 413 545 1200.

E-mail address: mathias@geo.umass.edu (M. Vuille).

0921-8181/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.gloplacha.2007.11.003

spring and early summer, is negligible in the tropics, leaving glaciers as the only major water reservoir.

Roughly 70% of all tropical glaciers are located in Peru. The most extensively glaciated mountain range within Peru is the Cordillera Blanca (8°30’–10°10’S), which hosts nearly a quarter of all tropical glaciers (Fig. 1). The glacier shrinkage observed during the 20th century in this mountain range is substantial and has been documented in many studies (Kaser et al., 1990, 1996a; Hastenrath and Ames, 1995a,b: Kaser and Georges, 1997, 1999; Ames, 1998; Kaser, 1999; Georges, 2004; Mark and Seltzer, 2005a,b; Mark et al., 2005; Silverio and Jaquet, 2005; Raup et al., 2007; Young and Lipton, 2006;

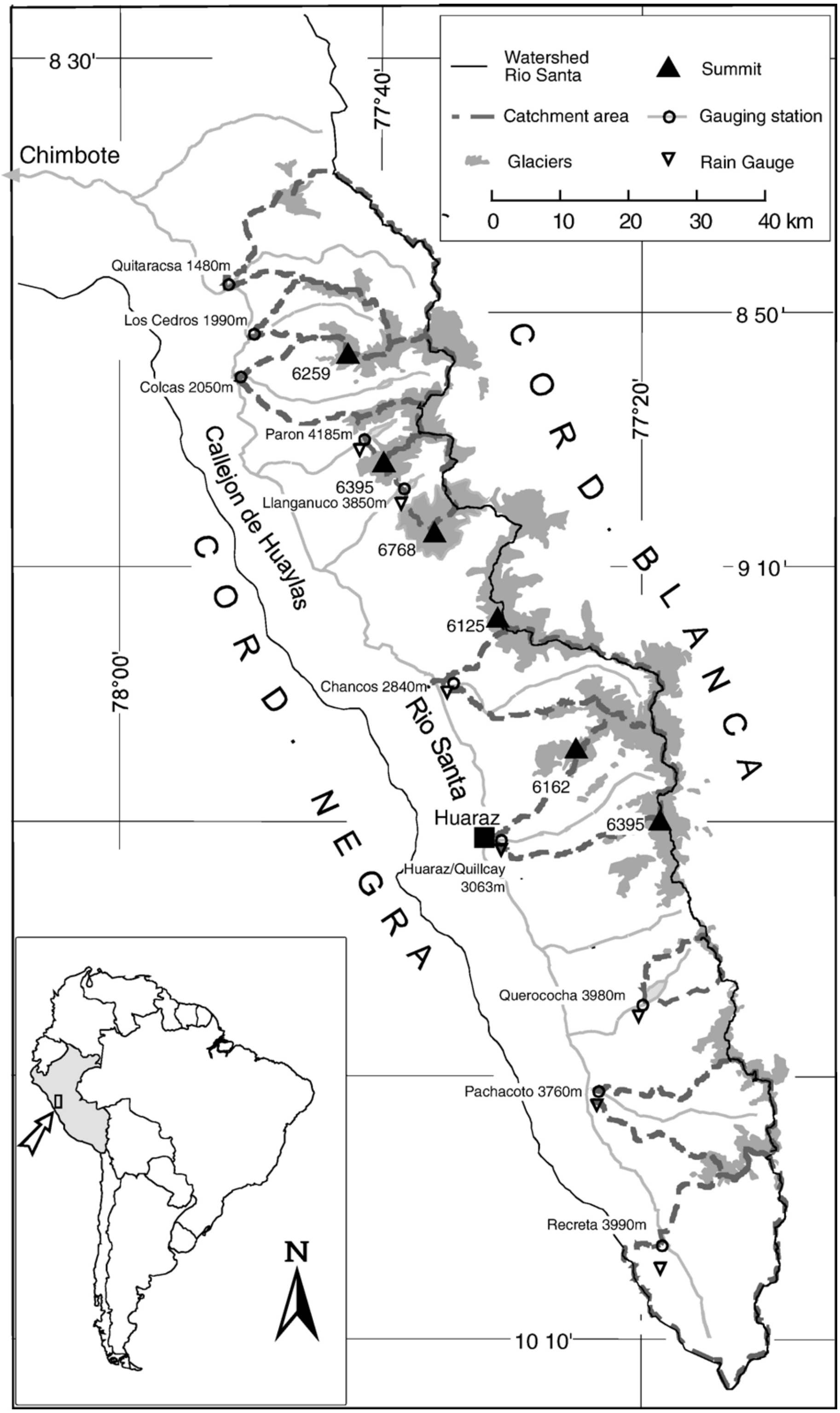

Fig. 1. Map of the Cordillera Blanca showing the main glaciers and catchments discussed in the text.

Lemke et al., 2007; Vuille et al., 2007). Georges (2004), in a comprehensive overview, estimated that the glacier-covered area had decreased from 800–850 km^2 in 1930 to 600 km^2 at the end of the 20th century. Modeling studies project that glaciers in the Cordillera Blanca will continue to shrink significantly over the next decades, and may disappear completely in some catchments by 2080, with drastic consequences for runoff (Juen et al., 2007). Streamflow may increase during the wet season but will decrease during the dry season, effectively enhancing the seasonal amplitude of runoff. While glaciers retreat and lose mass they also add to a temporary surplus in runoff, to which downstream users quickly adapt. Such an increase however is relatively short-lived and not sustainable once glaciers become small or eventually disappear (Jansson et al., 2003). Monitoring of glacier discharge from the Cordillera Blanca has shown that such changes are already taking place and that increased runoff is accompanied by glacier thinning and supplied by non-renewed glacier melt (Hastenrath and Ames, 1995b; Ames and Hastenrath, 1996; Mark and Seltzer, 2003; Mark et al., 2005).

Given the increase in glacier runoff and the terminus retreat observed throughout the Cordillera Blanca, it is clear that glaciers are not in balance with the regional climate. It is commonly assumed that tropical glaciers shrink in response to increased air temperature, which has indeed been observed in the region (Vuille and Bradley, 2000; Vuille et al., 2003; Mark and Seltzer, 2005a). There is also little doubt that a future increase in temperature on the order of 4–5 °C, projected by climate models based on several IPCC emission scenarios (Bradley et al., 2004, 2006), will have a significant impact on glacier distribution in the region (Juen, 2006; Juen et al., 2007). Detailed energy and mass balance studies on glaciers in the inner (Ecuador) and the outer tropics (Bolivia), however, show that temperature and the sensible heat transfer do not play such a dominant role as on mid-latitude glaciers. Instead radiative fluxes and the turbulent latent heat appear to dominate the glacier surface energy balance (Wagnon et al., 1999a,b). On glaciers in Bolivia for example, the amount and timing of precipitation (through its impact on albedo), atmospheric humidity (through its partitioning of the available energy into melt and sublimation) and cloud cover (controlling the incoming longwave radiation), appear to be more relevant (Francou et al., 2003). In the inner tropics near the equator studies by Favier et al. (2004b) and Francou et al. (2004) showed that in addition to the above mentioned factors, temperature may indeed play a pivotal role, but less so because of sensible heat transfer than through its impact on the rain–snow line. This line oscillates through the glacier ablation zone all year round and thereby determines whether the glacier snout is exposed to rain or snow.

On interannual timescales glacier mass balance in both Ecuador and Bolivia is strongly influenced by the El Niño–Southern Oscillation (ENSO) phenomenon. In Bolivia the impact of ENSO is primarily through its effect on precipitation variability (the Bolivian Altiplano generally experiences drought during El Niño), while glaciers in Ecuador are negatively affected by the higher temperature during El Niño and the associated increase in the rain–snow line (Francou et al., 2003, 2004). Hence the same climatic phenomenon (ENSO) has a similar impact on glaciers in Ecuador and Bolivia (negative mass balance during El Niño and positive or near-equilibrium during La Niña) but for different reasons (Favier et al., 2004a).

In Peru and in the Cordillera Blanca in particular, such analytical studies linking glacier mass balance variations with large-scale climate dynamics and atmospheric circulation anomalies have been sorely lacking. Unlike in Bolivia and Ecuador, where continuous monthly mass balance records exist, now covering more than a decade, such measurement programs were only initiated very recently in the Cordillera Blanca. Kaser et al. (2003), however, were able to reconstruct annual glacier mass balance records from the largest glaciers in the Cordillera Blanca based on runoff measurements from stream gauges between 1953 and 1993. Given the importance of the glaciers in the Cordillera Blanca for water resources downstream, a better understanding of glacier–climate interactions in the region is desperately needed. The goal of this paper is therefore to assess, for the first time, how mass balance variability in the Cordillera Blanca is linked to the large-scale circulation, to investigate what climate parameters (temperature, precipitation, atmospheric humidity, etc.) are most relevant to understand and predict glacier variations, and to document whether ENSO plays a similar pivotal role in determining interannual mass balance variability as in other parts of the tropical Andes.

In the next section we present the data and methods used in this study. Section 3 shows how regional- and large-scale climate affects glacier mass balance variability in the Cordillera Blanca, while Section 4 discusses why these relationships hold in most, but not all years, and how the results differ from similar previous studies in Ecuador and Bolivia. Section 5 ends with a summary and some concluding remarks.

2. Data and methods

While glacier terminus retreat on some smaller glaciers in the Cordillera Blanca has been documented annually since the 1960s (Ames et al., 1989), no long and continuous mass balance measurements exist. Ablation measurements were started on several glaciers in the early 1970s, in particular on Yanamarey and Uruashraju glaciers, but attempts to measure accumulation were not successful (Kaser et al., 1990). Instead mass balance was reconstructed indirectly based on runoff records from the region by Kaser et al. (2003). Here we use their 41-year-long annual mean mass balance time series from 1953 to 1993, established for 5 glaciated subcatchments which drain the Cordillera Blanca, namely Pachacoto, Huaraz/Quillcay, Chancos, Llanganuco and Paron (Fig. 1). Mass balance time series were reconstructed for these catchments based on monthly runoff (Q) and precipitation (P) measurements, assuming that any changes in catchment storage (P–Q) are due to changes in glacier mass (Kaser et al., 2003). Evaporation (E) outside the glaciated area was assumed to be 1 mm day^{-1}. The reconstructed cumulative mass balance time series (Fig. 8 in Kaser et al., 2003) show a significant negative trend, due to predominantly negative annual mass balance data. This negative trend was only briefly interrupted by net mass gain in the early 1970s (Kaser et al., 2003). This is consistent with observations on glacier terminus variations, adding confidence to the reconstruction and indicating that glaciers in the Cordillera Blanca react quickly to changes in mass balance with a time lag of only a few years. It is important to note that the reconstruction method chosen by Kaser et al. (2003) only works in catchments where glaciers are the sole major water reservoir. Therefore the catchments Quitaracsa, Los Cedros, Colcas, Querococha and Recreta (Fig. 1) were excluded from the analysis by Kaser et al. (2003) because: (1) they contain other reservoirs such as large swamps; (2) they were impacted by human constructions such as irrigation channels or artificial lake outlets or; (3) their degree of glaciation was simply too low, thereby blurring the dominant impact of glaciers on runoff downstream. According to Kaser et al. (2003) the remaining 5 catchments (Pachacoto, Huaraz/Quillcay, Chancos, Llanganuco and Paron) used in this study, in 1990 had a total ice coverage of 125.6 km^2, which equals 72.4% of the total ice coverage (173.4 km^2) of the 10 Cordillera Blanca subcatchments shown in Fig. 1. While this mass balance reconstruction was performed on a monthly basis, the lack of seasonal variations in the evaporation estimate introduces a significant uncertainty in individual monthly values, but the impact on interannual variations is relatively minor (Kaser et al., 2003). We therefore restrict our analysis to annual timescales, based on the hydrologic year, October–September.

Precipitation in this region is dominated by the southward expansion of the upper-tropospheric easterlies during austral summer, associated with the intensification of the South American summer monsoon (Garreaud et al., in press). Annual mean precipitation shows a significant north–south gradient with 770 mm y^{-1} to the north (Paron), but only 470 mm·y^{-1} in the south (Recreta). On average 90% of the annual total precipitation falls within the seven wet and transition season months from October to April (ONDJFMA), with a peak in precipitation in February and March. The rest of the year (May–September) is rather dry, with less than 50–100 mm total precipitation. Given this seasonality of precipitation, it is clear that accumulation on the glaciers occurs mainly during ONDJFMA. Ablation on the other hand takes place all year round, but it is equally reduced during the dry season because of enhanced sublimation, which limits melting.

Hence mass turnover, reflected in the annual mass balance, occurs primarily during the wet and transition seasons. Although we are aware that the dry season also has some influence on the annual mass balance, in the following sections we therefore consider the hydrologic year mass balance time series as representative of wet and transition season conditions and compare them with local, regional- and large-scale climate variability during the seven months ONDJFMA.

The mass balance time series from Kaser et al. (2003) is shown in Fig. 2. Since this time series shows individual, rather than cumulative mass balance, there is no apparent negative trend. Because the location, hypsometry and degree of glaciation vary considerably between the five catchments, the variance of the individual time series is different. To assure that all catchments are weighted equally, we created an averaged mass balance based on the standardized individual time series. We further removed outliers, which showed departures of more than ± 1.5 standard deviations from the mean (Fig. 2). While this threshold is admittedly subjective, it helps to increase the signal to noise ratio of the time series. More than half of the outliers stem from the southernmost Pachacoto catchment, which in many years showed a behavior that was not in tune with the rest of the Cordillera Blanca. This anomalous behavior of the Pachacoto catchment may be related to a north–south climatic gradient and the location of Pachacoto near the southern end of the Cordillera Blanca, or the fact that its catchment is only 9.7% glacier-covered, compared with 17.4–40.9% glaciated area in the other catchments (all data refer to 1990 glaciation; Kaser et al., 2003).

In the next section we search for significant relationships between the Cordillera Blanca mass balance time series shown

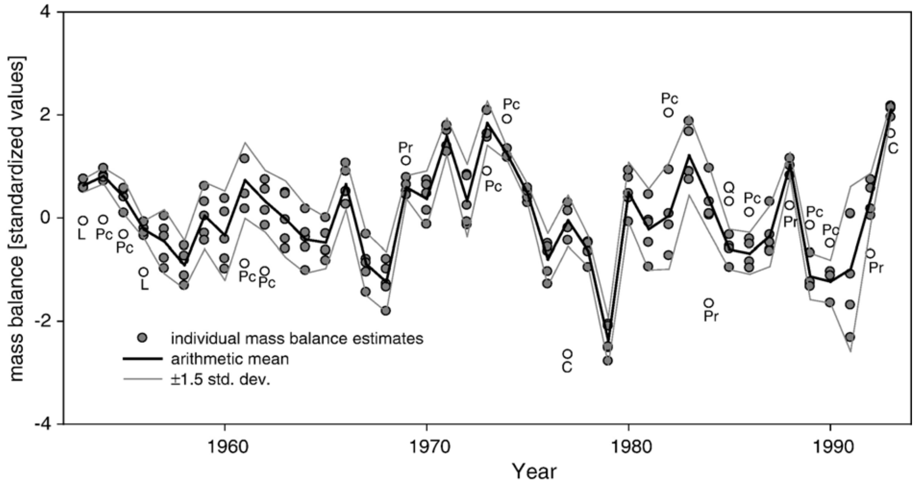

Fig. 2. Cordillera Blanca standardized mass balance time series between 1953 and 1993. Years indicate hydrologic year between October and September, i.e. 1953 indicates time period between Oct. 1953 and Sept. 1954. Dots represent individual values from 5 glaciated watersheds (Kaser et al., 2003). Thick black line indicates regional average with outliers (white dots) excluded. Outliers are defined as values that are outside ± 1.5 standard deviations (thin gray lines). Labels near outliers indicate which catchment outlier stems from: Pachacoto (Pc), Huaraz/Quillcay (Q), Chancos (C), Llanganuco (L), or Paron (Pr).

in Fig. 2 and various regional- to large-scale climate variables and diagnostics. These include station data of monthly mean temperature and monthly precipitation totals from Peru, obtained from the Peruvian national meteorological service (SENAMHI), the Peruvian Institute for Natural Resources (INRENA) or extracted from the Global Historical Climatology Network (GHCN) data base (Peterson et al., 1998). All data were quality-controlled based on difference time series with homogenized reference stations (Vuille and Bradley, 2000; Vuille et al., 2003). Only years with complete wet season data (ONDJFMA) were considered and only stations which had at least 20 (30) years worth of complete data coverage between 1953 and 1993 were included in the temperature (precipitation) analysis.

Besides snowfall and temperature, atmospheric humidity is commonly considered to be a crucial variable for glacier mass balance, as humidity controls the partitioning of the incoming available energy (directed toward the glacier surface) into melt and sublimation. On the few glaciers studied, it has been observed that increased humidity during the wet season is at least in part responsible for the higher melt rates at that time of year (e.g. Wagnon et al., 1999a). No long and reliable station records of atmospheric humidity exist in the Peruvian Andes, so we instead made use of gridded vapor pressure (*e*) from the CRU TS 2.1. data set (Mitchell and Jones, 2005). However, over regions such as Peru, where no station input data exists, the CRU TS 2.1 data is instead based on synthetic data using predictive relationships with primary variables (New et al., 2000). Hence considerable caution is warranted when interpreting the results based on such data alone.

To assess whether and how mass balance in the Cordillera Blanca responds to variations in tropical SSTs and changes in the large-scale circulation, we made use of a number of global, gridded products. We used the NOAA Extended Reconstructed SST (ERSST V2) data set, provided as monthly means on a 2° × 2° grid (Smith and Reynolds, 2004). To characterize ENSO conditions we took advantage of the Niño-3.4 index, defined as SSTA averaged over the region 5°S–5°N and 170°–120°W. Tropospheric temperature, wind field, geopotential height, vertical velocity (ω) and relative humidity on various diagnostic levels were extracted from the NCEP–NCAR reanalysis data base (Kalnay et al., 1996). This is a commonly used product, containing global gridded fields on a 2.5° × 2.5° resolution, produced by a frozen assimilation system and updated every 6 h with surface, satellite and radiosonde observations. It is widely applied in climate dynamics studies given its many advantages, such as temporal continuity, global coverage and physical consistency. It has, however, also a number of drawbacks, in particular the changes in the observational input over time, which may lead to spurious, non-physical trends in the data. Therefore this kind of data is well suited for studies of interannual variability, but its ability to capture multidecadal or longer trends is marginal at best. Another limitation is the lack of observed precipitation data in the reanalysis, which is instead simulated and therefore model-dependent. Hence the reanalysis precipitation is internally consistent with the other fields, but it is of rather poor quality over the South American tropics (e.g. Costa and Foley, 1998; Liebmann et al., 1998). We therefore rely on monthly NOAA interpolated Outgoing Longwave Radiation (OLR) data (Liebmann and Smith, 1996), available since 1974 on a 2.5° × 2.5° grid and on data from the Global Precipitation Climatology Product (GPCP), which is based on precipitation data, merged from rain gauge and satellite estimates (Adler et al., 2003). Since the analyses with these two products yielded almost identical results, but OLR covers a longer time period (available since 1974 as compared to 1979 for GPCP), we only discuss the results based on the OLR analysis in Sections 3 and 4. OLR is a proxy for convective precipitation as it is an indicator of the amount and height of clouds over a given region and time. Several studies have analyzed the relationship between precipitation, OLR and convective activity over tropical South America (e.g. Liebmann et al., 1998; Chen et al., 2001). They have shown that OLR is low when deep convective clouds, which are high in the atmosphere and thus cold, are present. During the dry season on the other hand, OLR is influenced by other factors, such as boundary-layer processes, low-level clouds, water vapor and surface temperature. Since we limit our analysis to the wet season, these factors did not play a significant role, which is corroborated by the close agreement between results obtained from OLR and GPCP.

3. Results

3.1. Relationships with regional-scale climate

Even though temperature is not the most relevant variable of the glacier energy balance, neither in Bolivia nor in Ecuador, it is still significantly correlated with mass balance on interannual timescales at both locations. Francou et al. (2003, 2004) argued that this relationship between temperature and mass balance is

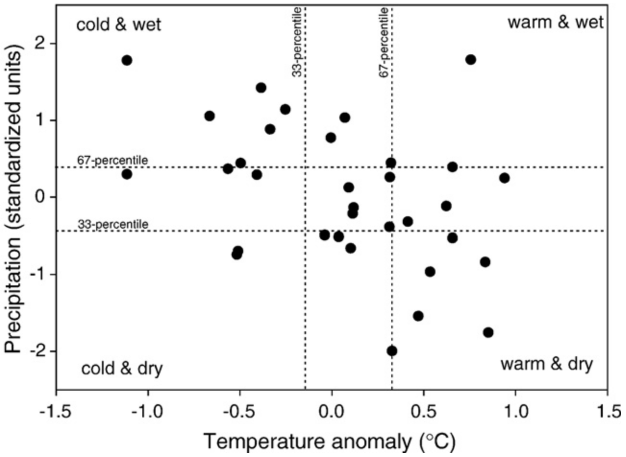

Fig. 3. Scatterplot of ONDJFMA precipitation and temperature anomalies between 1961 and 1993. Reference period for anomalies is 1961–90. Temperature data is extracted over the Cordillera Blanca region from the Vuille and Bradley (2000) data set. Precipitation data is average from standardized precipitation records from Huaraz, Llanganuco and Paron. Correlation between precipitation and temperature is −0.41, significant at $p = 0.05$. Dashed lines indicate the 33 and 67 percentiles for both records, used to bin the data into cold, neutral, warm (temperature) and dry, neutral, wet (precipitation), respectively.

caused by the role of temperature as an integrating factor of climate, being strongly related to other more important variables, such as humidity, cloud cover or precipitation. In the Cordillera Blanca, as in much of the tropical Andes, diagnostic studies trying to separate the effects of temperature and precipitation on glacier mass balance are complicated by the significant covariance between the two variables on interannual timescales. Throughout much of the tropical Andes wet years tend to be cold, while warm years are predominantly dry (Vuille et al., 2000a; Garreaud et al., 2003). This situation is no different in the Cordillera Blanca as can be seen in Fig. 3, where anomalies of ONDJFMA precipitation and temperature are plotted over a 33 year period (1961–1993). The temperature data was extracted from the gridded temperature reconstruction by Vuille and Bradley (2000), while precipitation is based on the standardized average from Huaraz, Llanganuco and Paron. The correlation between temperature and precipitation is −0.41, significant at $p = 0.05$. More importantly, when binning the data into three equal segments (terciles) of 11 warm, neutral and cold years (wet, neutral and dry years for precipitation, respectively), it is apparent that only 4 years (12%) fall into the cold/dry or warm/wet category, while cold/wet or warm/dry years occurred with a three times higher likelihood (12 years or 36% of the time). In other words, cold years are three times as likely to be wet than dry and warm years have a three times higher chance of being dry than of being wet. This behavior makes the attribution of mass balance variations to individual climate parameters more difficult, because years with increased accumulation are also commonly characterized by reduced melt, while ablation is usually enhanced in years when snowfall is already low.

Nonetheless it is worthwhile to analyze how mass balance correlates with individual parameters in the Cordillera Blanca. Fig. 4a shows the spatial correlation between interannual variations in mass balance and temperature, recorded by the Peruvian meteorological network. The results suggest that a weak but significant ($p < 0.05$) negative correlation exists between the two parameters on interannual time scales in the Cordillera Blanca region. Correlations with temperature elsewhere in the country are also predominantly negative, but mostly insignificant, in particular to the south. Hence temperature may indeed be a relevant factor to explain mass balance variability, but its significance appears to be limited to the immediate surroundings of the Cordillera Blanca. The correlation analysis with precipitation on the other hand, yields a relationship which is highly significant ($p < 0.01$) throughout the Peruvian Andes and even in the Altiplano region near the Peru–Bolivia border (Fig. 4b). This suggests that ONDJFMA precipitation is a more important variable for explaining mass balance variability in the Cordillera Blanca region, and that the climate signal embedded in the glacier mass balance record is not just of local, but at least of regional significance. It also shows that precipitation variability in the Peruvian Altiplano near Lake Titicaca (15°S–17°S) and in the Cordillera Blanca (8°–10°S) show a coherent behavior on interannual timescales, which is likely driven by the same large-scale atmospheric forcing. From this analysis, however, it remains debatable whether the significant positive relationship between precipitation and mass balance is primarily due to the direct impact of precipitation (accumulation), or rather indirectly due to changes in the albedo and the net-shortwave radiation receipts at the glacier surface. Most likely both factors are at play, but since the record derived by Kaser et al. (2003) considers mass balance integrated over the entire catchment, direct accumulation processes are probably more relevant than in the studies by Francou

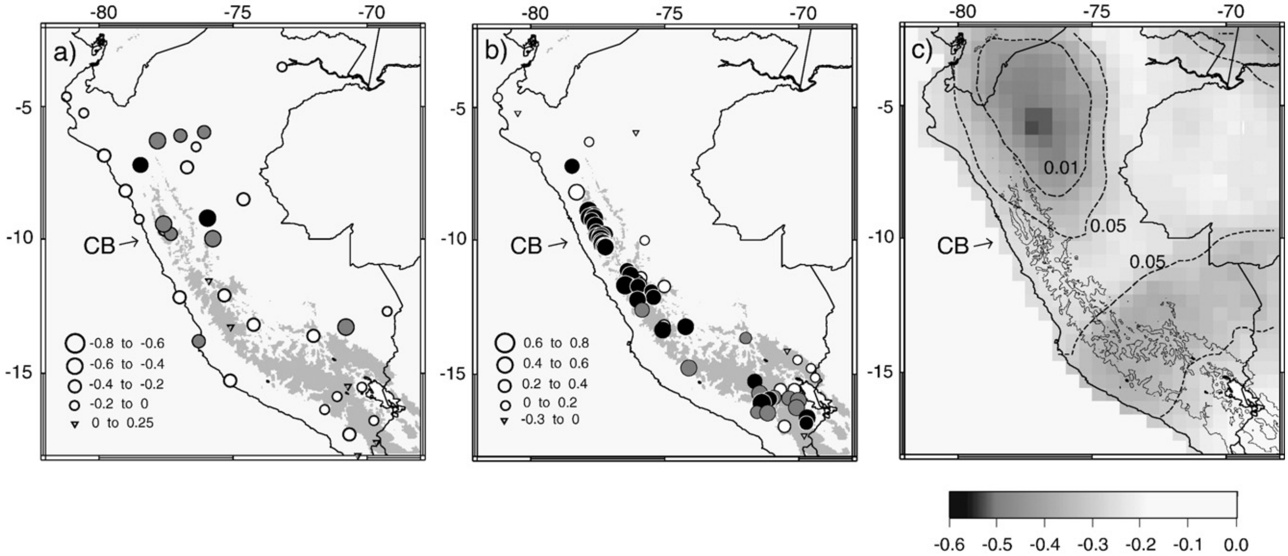

Fig. 4. Correlation between annual (Oct.–Sept.) Cordillera Blanca mass balance time series and austral summer (ONDJFMA) (a) near-surface (2 m) air temperature, (b) precipitation amount and (c) near-surface water vapor pressure between 1953 and 1993. Correlations in (a–b) are based on 36 (temperature) and 65 (precipitation) stations records from Peru, respectively. Only stations which contain at least 20 (30) years worth of temperature (precipitation) data were included. Size of correlation in (a–b) is proportional to size of symbol (see legend in lower left of each figure); correlations significant at $p < 0.05$ ($p < 0.01$) are indicated by gray (black) circles. (c) is based on CRU TS 2.1 data. Dashed lines indicate correlations significant at $p < 0.05$ and $p < 0.01$ respectively. Elevations >4000 m are indicated by gray shading (a–b) or black contour line (c). Location of Cordillera Blanca (CB) is indicated by arrow.

et al. (2003, 2004), which focused on data derived from a stake network in the ablation zone only (Antizana, Ecuador) or from a small, low-elevation glacier which had already lost its entire accumulation zone (Chacaltaya, Bolivia). Fig. 4c shows the same correlation analysis for vapor pressure, derived from the gridded CRU TS 2.1 data set. The results suggest that there is a significant negative relationship between Cordillera Blanca mass balance and near-surface vapor pressure, which is consistent with observational studies from glaciers in Bolivia. Increased near-surface humidity reduces the vapor pressure gradient between the glacier and the air above, thereby lowering the latent heat flux. As a result sublimation is limited and the available radiative energy is directly consumed by melting, which is about 8.5 times more energy efficient than sublimation, causing higher overall mass loss (Kaser et al., 1996b, 2005; Wagnon et al., 2001; Sicart et al., 2005). The relationship portrayed in Fig. 4c is therefore physically consistent with our understanding of the tropical glacier energy balance, but the spatial pattern of the correlation field is troubling. Highest correlations are observed to the northeast, near 6°S and not in the Cordillera Blanca region itself, where correlations just barely reach the 0.05 significance level. This spatial pattern is likely an artifact of the poor data coverage in the region and resulting errors in the interpolation scheme, as there is no reason why correlations should be less significant in the Cordillera Blanca than further north. Correlation analyses with CRU TS 2.1 precipitation and temperature fields yield similar spatial errors (not shown), arguing for caution in using this data set over such a data-void region as the Peruvian Andes.

3.2. Relationship with ENSO

Very little is known about interannual climate variability in the Cordillera Blanca region and how it relates to the large-scale atmospheric circulation. There are however a number of studies which have documented the significant impact of ENSO on temperature and precipitation in various regions of the tropical and subtropical Andes (e.g. Vuille, 1999, 2000a,b, 2003; Garreaud and Aceituno, 2001; Francou et al., 2003, 2004; Garreaud et al., 2003, in press; Vuille and Keimig, 2004). All studies conclude that El Niño events are characterized by above average temperature and reduced precipitation, while opposite conditions prevail during La Niña events. Given the significant relationship between glacier mass balance and regional temperature and precipitation fields documented in the previous section, it is worthwhile to see how glacier mass balance in the Cordillera Blanca responds to ENSO and tropical Pacific SSTA. We first compare the mass balance time series with the ONDJFMA Niño-3.4 index, which is a commonly used index to characterize ENSO conditions in the tropical Pacific (Trenberth, 1997). Fig. 5 shows that there is a good overall correspondence between the two time series ($r = -0.52, p < 0.001$) with negative mass balance anomalies during El Niño phases and positive mass balance anomalies during La Niña events. Hence the general response is the same as observed in Ecuador and in Bolivia (Francou et. al., 2003, 2004). A closer inspection of Fig. 5, however, indicates that this relationship was much stronger in the early part of the record and has weakened over the last 15–20 years. Before 1977 for example, the correlation is highly significant ($r = -0.63, p < 0.001$), but thereafter it is not ($r = -0.39$, insignificant at $p < 0.1$). This may be related to changes in the ENSO-behavior associated with the Pacific climate shift in the mid-1970s, or due to a weakened teleconnection during the positive phase of the Pacific Decadal Oscillation (PDO, Mantua et al., 1997). Another view is to consider that the basic relationship has remained unchanged, but that the second half of the record is being influenced by a few outlier years, in which the relationship between ENSO and mass balance does not hold. This contrast between ENSO and mass balance response is particularly notable in Fig. 5 during 1979/80 (most negative mass balance of the entire record despite only weak El Niño conditions), 1982/83 (near-normal mass balance in spite of strongest El Niño of the entire record) and 1993/94 (strongest

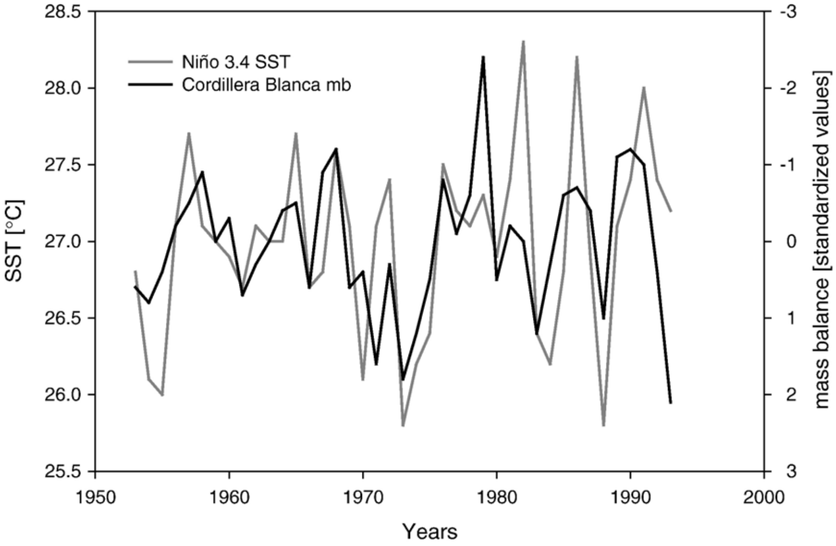

Fig. 5. Correlation between annual (Oct.–Sept.) Cordillera Blanca mass balance time series in black (standardized values) and ONDJFMA Niño-3.4 index in gray (in °C). Years refer to OND part of the year; hence 1960 refers to 1960/61. Please note that scale for mass balance is reversed.

positive mass balance of the entire record, despite neutral ENSO conditions). The view that the general relationship does still hold, but is biased by a few outliers, is supported by the fact that the correlation is equally strong after 1977 ($r = -0.68$, $p < 0.01$) if these three outliers are omitted. It does, however, beg the question why the predictive relationship between ENSO and glacier mass balance in the Cordillera Blanca falls apart in certain years. In this context it is also noteworthy that Kaser et al. (2003) came to similar conclusions in their analysis, when comparing the mass balance record with the Southern Oscillation Index (SOI). However, Kaser et al. (2003) did not attempt to explain why the relationship holds in most, but not all years. Here we will first focus on the general mechanism that causes mass balance anomalies to be negative during El Niño and positive during La Niña events, but we will revisit the question of why this teleconnection mechanism breaks down in certain years in Section 4.

3.3. Influence of large-scale climate dynamics

Consistent with the time series analysis in Fig. 5, the spatial correlation pattern in Fig. 6a indicates significant negative correlations between Cordillera Blanca mass balance and tropical Pacific SSTs, throughout the central equatorial Pacific, extending westward across the dateline and northeast and southeast toward the coasts of North and South America respectively. At the same time significant positive correlations extend in a typical V-shaped fashion from the western Pacific warm pool toward the subtropical North and South Pacific. This pattern is reminiscent of the typical ENSO mode and confirms the previous results of a negative mass balance when the central tropical Pacific is anomalously warm and vice-versa. Fig. 6b shows the correlation field for mid-tropospheric (500 hPa) temperature. Correlations are negative throughout the tropics and significant over much of the tropical continent, including the tropical Andes and the Cordillera Blanca region, as well as over most of the tropical Pacific. The lack of a significant correlation in the subtropics and the outer tropical Andes of southern Peru is consistent with the results from station data, depicted in Fig. 4a. The negative temperature correlation field over the tropical continent and over the eastern equatorial Pacific is in stark contrast to the positive correlations further south over the Southeast Pacific. This pattern effectively describes a weakened meridional temperature gradient and hence a relaxation (easterly anomalies) of the subtropical jet (Fig. 6c). The regression field of 250 hPa geopotential height and wind in Fig. 6c depicts the strength, sign and significance of atmospheric circulation anomalies at each grid point, associated with a one standard deviation variation in the Cordillera Blanca mass balance record. Hence it portrays the atmospheric conditions under which the mass balance in the Cordillera Blanca is above average, while during periods of negative mass balance anomalies the fields are essentially reversed. Overall the regression field is very reminiscent of the canonical ENSO cold phase, with the distinctive twin cyclones straddling the equator over the central equatorial Pacific at 15°S and 15°N (Yulaeva and Wallace, 1994). More importantly, Fig. 6c clearly documents that easterly

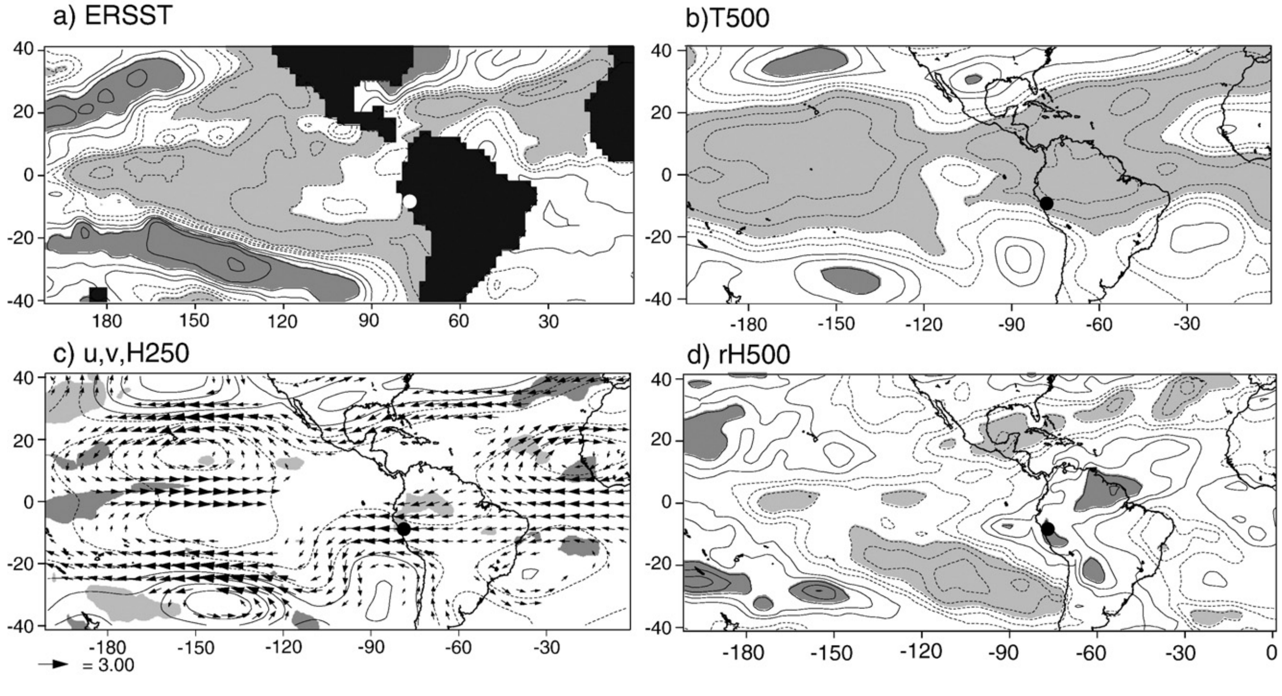

Fig. 6. (a) Correlation between annual (Oct.–Sept.) Cordillera Blanca mass balance time series and austral summer (ONDJFMA) SST, with significant ($p < 0.05$) positive (negative) correlations shaded in dark (light) gray. Contour interval is 0.1, negative contours are dashed and 0-contour is omitted. (b) as in (a) but for 500 hPa temperature. (c) as in (a) but for regression field of 250 hPa wind field and geopotential height and correlation with OLR (1974–93 only, with 1977–78 missing). Wind vectors are only plotted where correlation of mass balance with either zonal or meridional component is significant at $p < 0.05$. Scale for wind vector (in m s^{-1} per std. dev.) is shown in lower left. Contour interval for geopotential height is 4 gpm per std. dev.; negative contours are dashed. Light (dark) gray shading indicates significant ($p < 0.05$) negative (positive) correlation with OLR. (d) as in (a) but for 500 hPa relative humidity. White and black dots in all figures indicate location of Cordillera Blanca.

wind anomalies prevail over the tropical and subtropical Andes, including the Cordillera Blanca region as a result of the weakened meridional temperature gradient. Such anomalous upper-level easterlies have been linked to positive mass balance anomalies in Bolivia (Francou et al., 2003), southern Peru (Hastenrath et al., 2004), and to enhanced precipitation and snow accumulation in the Altiplano region (Vuille et al., 1998; Vuille, 1999; Garreaud and Aceituno, 2001). However, it is not the upper-level easterlies per se which transport the moisture, as the air at those altitudes is too cold to provide for a significant moisture influx. Instead this anomalous flow over the Andes, through downward mixing of easterly momentum, enhances moisture advection in near-surface levels from the continental lowlands (Amazon basin) to the east and thus leads to wet conditions in the high Andes (Garreaud, 1999). Significant negative correlations with OLR, indicative of enhanced convective activity over the Peruvian Andes (Fig. 6c) support this notion, even though this pattern is based on data after 1974 only, when the relationship with ENSO is weak. Mid-tropospheric relative humidity levels further confirm the results based on OLR, as they are also significantly higher in the Peruvian Andes during periods of positive mass balance (Fig. 6d). It is important in this context to draw a clear distinction between processes at the glacier surface and in the large-scale mid- and upper-tropospheric circulation. As discussed previously, increased humidity in near-surface levels can cause enhanced melt, when the reduced vapor pressure gradient between ice and surface air reduces sublimation but instead enhances melt. This process is important in the ablation zone of a glacier and only when temperatures are at or above freezing. On a large-scale, however, snowfall (and hence accumulation) is associated with an increase in free tropospheric relative humidity levels.

In summary the results in Fig. 6 suggest that the dynamic mechanism linking tropical Pacific SSTA with mass balance in the Cordillera Blanca is similar to the one described previously for the Altiplano region (Francou et al., 2003; Garreaud et al., 2003; Vuille and Keimig, 2004). This result is of considerable relevance because it clearly documents that mass balance anomalies in the Cordillera Blanca a) respond to fluctuations in large-scale climate, b) are dominated by climatic conditions in the tropical Pacific, c) are primarily recording changes in atmospheric circulation linked to precipitation variability and d) appear to be sensitive to the same circulation mechanism established previously for the central Andes (Altiplano) region.

To zoom in a bit closer on the Cordillera Blanca region we next discuss similar regression fields in a longitude–altitude cross-section along a transect across the Cordillera Blanca at 10°S from 65°W to 85 °W (Fig. 7). The upper-tropospheric easterlies are significant throughout the cross-section down to about 400 hPa (Fig. 7a). Moisture influx likely takes place at a lower level, but this process is not resolved by the reanalysis data in this region of complex topography. Mass balance is also significantly positively correlated with relative humidity, as already shown in Fig. 6d. Over the peaks of the Cordillera relative humidity is 2.5% higher per unit increase in the mass balance time series (Fig. 7b). It appears that the enhanced relative humidity during periods of positive mass balance is not

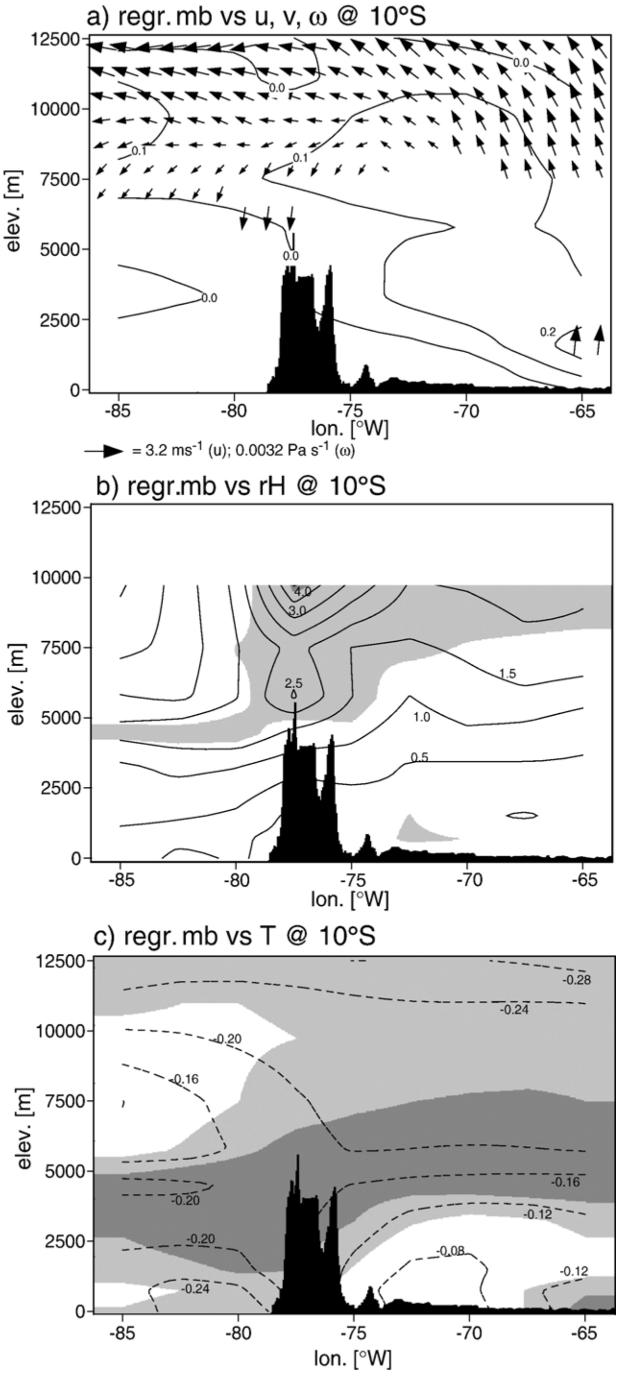

Fig. 7. Regression of annual (Oct.–Sept.) Cordillera Blanca mass balance with ONDJFMA tropospheric circulation along an east–west section across the Andes from Pacific (85°W) to Amazon (65°W) along 10°S from surface to 12500 m (200 hPa level). (a) Regression with zonal wind and vertical velocity (vectors) and meridional wind (contours). Vectors are only plotted where correlation of mass balance with either zonal wind (u) or vertical velocity (ω) is significant at $p<0.05$. Scale for vectors (in m s^{-1} per std. dev. and Pa s^{-1} per std. dev. respectively) is shown in lower left. Contour interval for meridional wind is 0.1 m s^{-1}. (b) Regression with relative humidity. Contour interval is 0.5% per std. dev. Significant correlations at $p<0.05$ ($p<0.01$) are indicated with light (dark) gray shading. Please note that humidity data is not available above 300 hPa (~9700 m). (c) Regression with temperature. Contour interval is 0.04 °C per std. dev., negative contours are dashed and significant correlations at $p<0.05$ ($p<0.01$) are indicated with light (dark) gray shading. Black shading in all figures represents Andean topography.

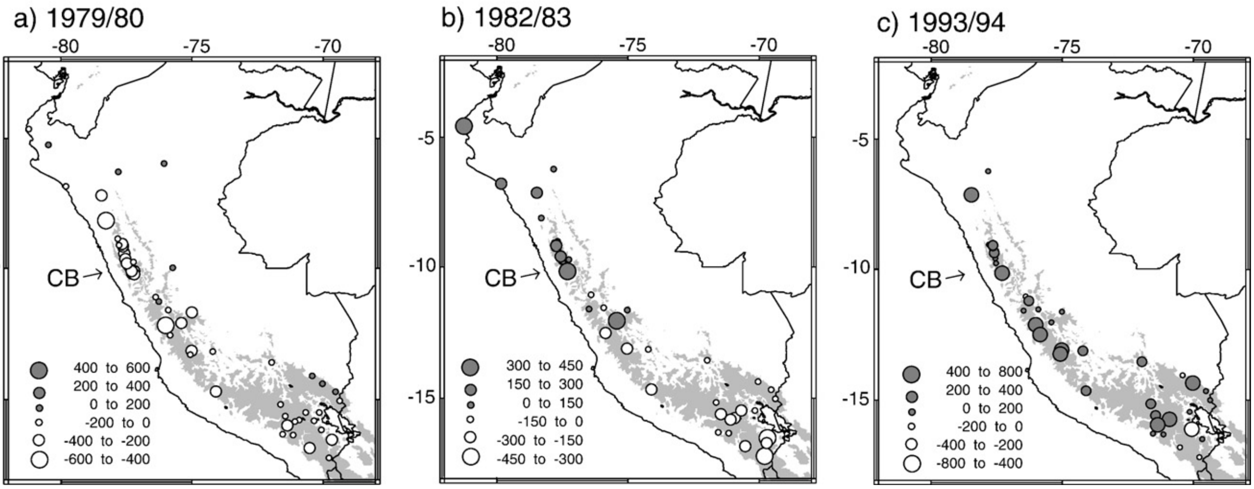

Fig. 8. Precipitation anomalies in Peru (in mm) for austral summers (ONDJFMA) 1979/80 (left), 1982/83 (middle) and 1993/94 (right) as recorded by station data. Size of circles is proportional to size of anomaly; positive anomalies are shown in gray, negative anomalies in white (see scale in lower left of each Figure). 57, 47 and 39 station records were available for analysis in Figures (a), (b) and (c), respectively. Please note that scale is different in each Figure. Reference period for anomalies is 1961–90. Elevations >4000 m are shaded gray. Location of Cordillera Blanca (CB) is indicated by arrow.

primarily in response to enhanced water vapor influx, as specific humidity changes are insignificant (not shown), but probably more so due to the decrease in temperature, which is on average reduced by −0.16 to −0.2 °C per unit increase in mass balance (Fig. 7c). Temperature is also the only variable where correlations with mass balance are not highest in the upper — but in the mid-troposphere, at the actual elevation of the glaciers.

4. Discussion

The previous section documented that mass balance variability in the Cordillera Blanca records changes in climate over the tropical Pacific domain, through interactions with the atmospheric circulation, which in many aspects resemble the teleconnection mechanism proposed for glaciers in the Bolivian Cordillera Real (Francou et al., 2003). It does not, however, explain why the relationship appears to have been much stronger in the early part of the record, while the 1980s and early 1990s saw a number of years where the relationship fell apart. Garreaud and Aceituno (2001) noted a similar occasional breakdown in the relationship between ENSO and summer precipitation in the Altiplano region. They attributed this decoupling of ENSO and precipitation variability to the high sensitivity of precipitation to the exact location and intensity of the upper-air zonal wind anomalies. As shown by Garreaud and Aceituno (2001) each ENSO event is somewhat unique and different from all the others in terms of its spatial pattern of SST anomalies in the Pacific. It is this pattern, which determines the location of the upper-level wind anomalies, and if it is unusual it will cause an anomalous location of the zonal wind anomalies over the Andes, thereby shifting precipitation anomalies away from their average location. This mechanism explains, for example, why the 1972/73 El Niño event was wet and the 1988/89 La Niña phase was dry in the central Andes (Garreaud and Aceituno, 2001). In the following section we therefore take a closer look at climate and atmospheric circulation during the three most anomalous years in the Cordillera Blanca, namely 1979/80, 1982/83 and 1993/94.

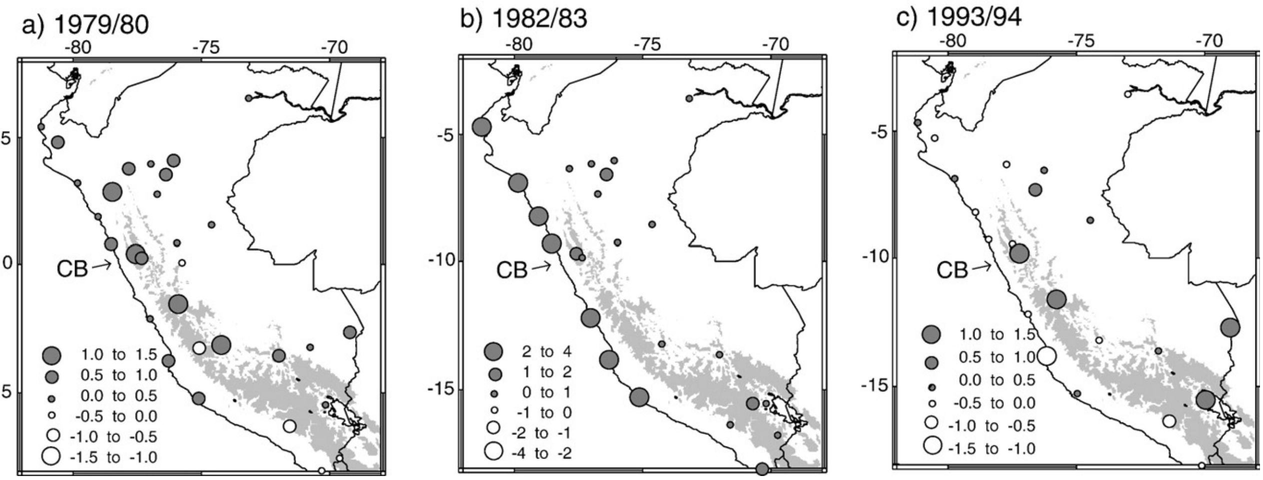

Fig. 9. As in Fig. 8 but for near-surface temperature anomalies (in °C). 31, 24 and 23 station records were available for analysis in Figures (a), (b) and (c), respectively.

In 1979/80 mass balance in the Cordillera Blanca was by far the most negative of the entire 41 years, despite only a weak El Niño event in the Pacific (Fig. 5). Indeed the entire Peruvian Andes suffered from below average precipitation, with a massive deficit on the order of 400–600 mm below average in most locations of the Cordillera Blanca (Fig. 8a). This large precipitation reduction was caused by the failure of the summer monsoon. Strong upper-level westerly wind anomalies, associated with a cyclonic anomaly centered off the coast of South America over the Southeast Pacific (Fig. 10a), inhibited moisture influx from the east throughout most of the wet season. Temperatures 0.5–1.5 °C higher than normal at the surface (Fig. 9a) and 0.5°–0.75 °C higher in the mid–troposphere (Fig. 11a), further contributed to the extremely negative mass balance in this year.

1982/83 saw the largest ENSO of the entire record and by some measures of the entire century, rivaled only be the event in 1997/98. Despite the anomalous conditions in the tropical Pacific, mass balance in the Cordillera Blanca was near-average (Fig. 5). The precipitation anomalies in Fig. 8b are very insightful and can help explain this apparent paradox. While the Altiplano region including southern Peru suffered from the lowest precipitation amounts seen in many decades, regions to the north of ~12°S received above average precipitation. The Cordillera Blanca for example had precipitation amounts which ranged anywhere from 0–450 mm higher than normal. This northwest–southeast see-saw in precipitation was of such large-scale that it can also easily be recognized in the OLR data (Fig. 10b), even though the area of enhanced convective activity (<−5 W m^{-2}) doesn't

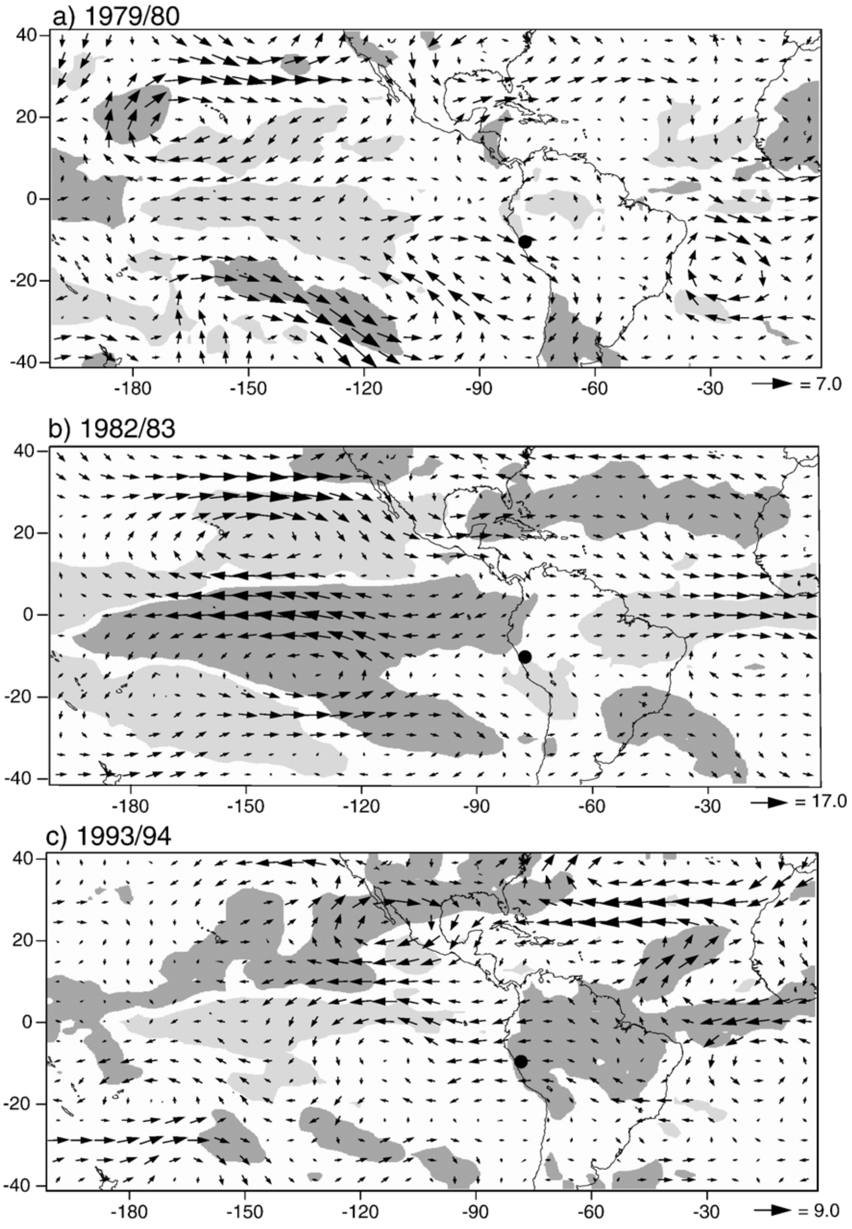

Fig. 10. Anomalies of outgoing longwave radiation, OLR (anomalies >5 W m^{-2} (<−5 W m^{-2}) shaded in light (dark) gray) and 250 hPa wind (vectors, in m s^{-1}) during ONDJFMA of (a) 1979/80, (b) 1982/83 and (c) 1993/94. Reference periods for anomalies are 1974–93 (OLR) and 1961–90 (wind) respectively. Note that scale for OLR is the same in all panels; but that vectors are scaled individually (see lower right of each panel). Black dots indicate location of Cordillera Blanca.

reach quite as far south as the observed precipitation anomalies on the ground. Temperature, as is typically the case during El Niño, was above average, but the largest positive departures were observed along the Pacific coast (2°–4 °C above average, Fig. 9b), while temperature anomalies in the Cordillera Blanca (0°–2 °C above average, Fig. 9b) and in the mid-troposphere (0.75°–1 °C above average, Fig. 11b) were more moderate. Nonetheless, the higher than normal temperature probably counterbalanced the increased precipitation to produce a near-normal annual mass balance.

The third year with a very unexpected mass balance response, 1993/94, featured the strongest positive mass balance of the entire record, despite neutral ENSO conditions (Fig. 5). Again the precipitation anomalies plotted in Fig. 8c provide the basis to explain this apparent contradiction. The entire range of the Peruvian Andes, with exception of the Lake Titicaca region, received abundant precipitation in 1993/94, with values of up to 800 mm above normal in the Cordillera Blanca. The wet conditions were part of a large-scale anomaly throughout the tropical Andes and much of the Amazon basin, as portrayed in the OLR anomaly field in Fig. 10c. The easterly wind anomalies in the upper troposphere along the entire Andean range from Bolivia to Ecuador are dynamically consistent with the wet conditions in the Cordillera Blanca. The temperature signal is

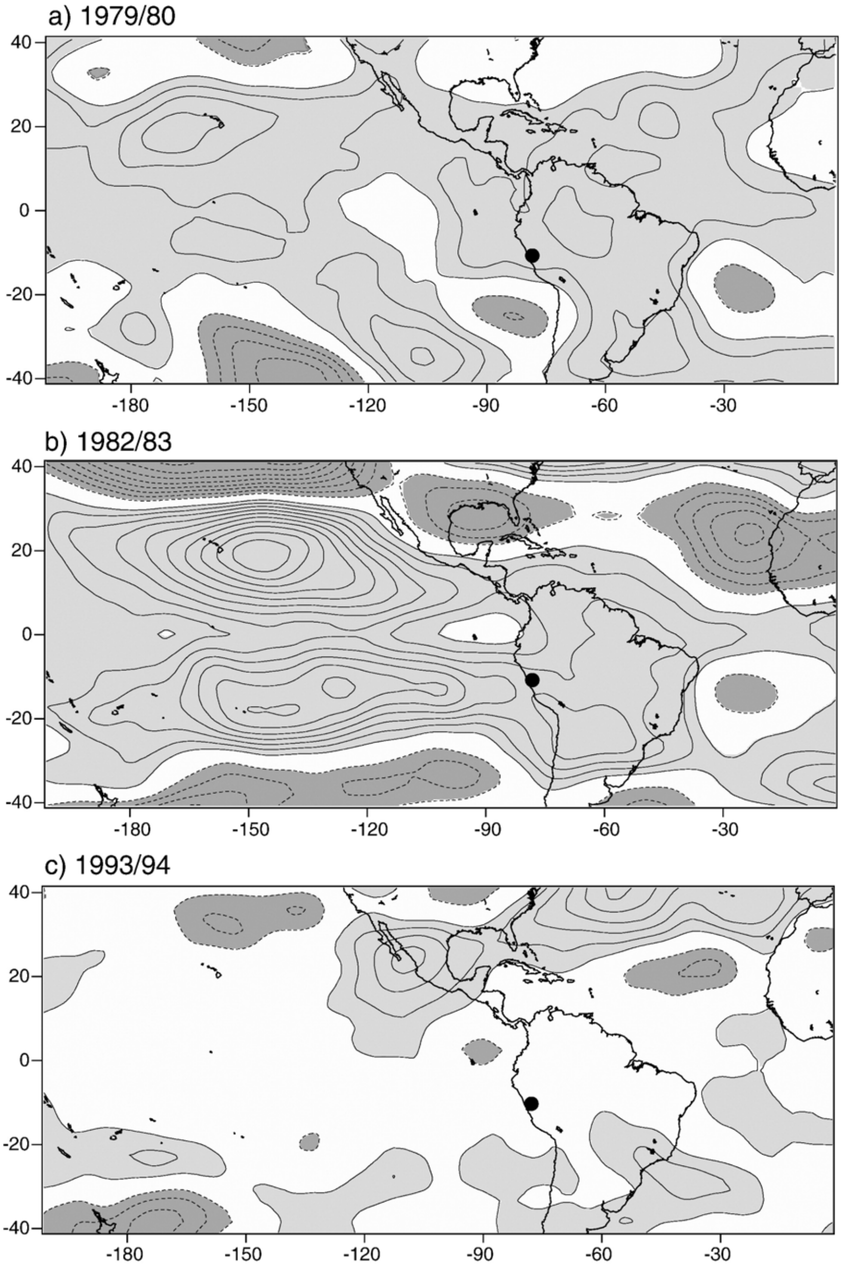

Fig. 11. As in Fig. 10, but for 500 hPa temperature and 1961–1990 reference period. Negative (positive) anomalies < −0.25 °C (> 0.25 °C) are shown in dark (light) gray. Contour interval is 0.25 °C; 0 °C-contour is omitted and negative contours are dashed.

much less pronounced with both positive and negative anomalies scattered throughout much of Peru. In the Cordillera Blanca the temperature response is equally inconsistent with stations reporting both below and above average temperatures (Fig. 9c). Mid-tropospheric temperatures do not show a strong signal and suggest that temperature was close to normal (Fig. 11c). This is further indication that mass balance variations are first and foremost driven by changes in precipitation and only to a second degree reflect temperature fluctuations.

In summary this analysis of individual years, which did not live up to the expectations put forth by the simple linear model displayed in Fig. 5, shows that ENSO, while important, is not the only relevant factor controlling mass balance–climate relationships in the Cordillera Blanca. During neutral ENSO conditions in particular, other factors may become more relevant and can lead to extreme mass balance anomalies, such as in 1993/94. In addition, our analysis shows that El Niño- or La Niña-related impacts on mass balance do not always follow the predicted linear relationship and that each ENSO event has its own characteristics which can change the teleconnection mechanism over the Cordillera Blanca region. The intensity and location of the upper-tropospheric zonal flow is crucial in determining the precipitation response in the Peruvian Andes. Similar results have been obtained previously for the Peru–Bolivia Altiplano region (Garreaud and Aceituno, 2001). The Cordillera Blanca located at ~10°S, is near the northern edge of the mean climatological position of the upper-air mechanism proposed by Garreaud and Aceituno (2001), and therefore this region is very susceptible to changes in its mean latitudinal position. This explains why the ENSO–mass balance relationship defies expectations more often than for example on glacier Chacaltaya in Bolivia, where the linear relationship appears to be more stable (Francou et al., 2003).

The strong influence of tropical Pacific SST patterns on the location of the upper-tropospheric easterlies (Garreaud and Aceituno, 2001) may also explain why the ENSO–mass balance relationship has weakened in the second half of the observation period, as ENSO characteristics appear to have undergone significant changes since the mid-1970’s (e.g. Trenberth and Hoar, 1996, 1997; Goddard and Graham, 1997; Trenberth and Stepaniak, 2001).

5. Summary and conclusions

Our study of mass balance variations in the Cordillera Blanca, Peru, shows that mass balance responds to fluctuations in large-scale climate, dominated by the conditions in the tropical Pacific. ENSO is the primary pace-maker on interannual timescales causing positive mass balance anomalies during La Niña and negative anomalies during El Niño events. Hence the response of glacier mass balance in this region is similar to what has been documented previously on glaciers to the south in Bolivia and to the north in Ecuador. Our results further indicate that the main mechanism linking ENSO with glacier mass balance is similar to the one discussed previously for Bolivia (Francou et al., 2003), but different from what was reported from Ecuador (Francou et al., 2004). Changes in the meridional temperature gradient between tropical and mid-latitudes, forced by ENSO-related tropical Pacific SST anomalies, disrupt the upper-tropospheric zonal flow aloft the Cordillera Blanca and induce westerly (El Niño) or easterly (La Niña) wind anomalies. This anomalous upper-tropospheric flow is responsible for the reduced (El Niño) or enhanced (La Niña) moisture influx from the east, producing anomalously dry or wet conditions respectively. This mechanism however, is more pronounced further south over the Bolivian Altiplano and does not affect the Cordillera Blanca in all ENSO years. This explains why ENSO does not show such a close linear relationship with mass balance in the Cordillera Blanca, as for example on Chacaltaya in Bolivia. Nonetheless our study indicates that glaciers in the Cordillera Blanca are recording changes in the large-scale atmospheric circulation linked to regional-scale precipitation variability. Whether the impact of precipitation on mass balance is mostly direct (through changes in snow accumulation) or also indirect (through changes in albedo and hence the net-shortwave radiation balance) can not be answered conclusively in this study. Temperature is probably of secondary importance and usually co-varies with precipitation (wet summers tend to be cold and dry summers tend to be warm), thereby enhancing the precipitation signal. In years when this is not the case, such as in 1982/83, the two variables may neutralize each other, thereby creating a near-average mass balance. The role of humidity still needs further investigation, which is currently hampered by the lack of long and high-quality measurements. Our results based on CRU TS 2.1 data suggest a significant negative impact of near-surface vapor pressure on mass balance, but this result could not be confirmed with reanalysis data. Both products suffer from the lack of sufficient input data in to their assimilation and interpolation schemes.

Our analysis provides a first step toward a better understanding of what drives glacier mass balance variability in this part of the world. Future studies should ideally be based on higher-resolution (monthly) data from actual stake networks to take into account seasonal variations. A detailed separate analysis of the transition seasons (e.g. the periods of onset and end of the wet season) is needed, as these periods can cause large mass balance fluctuations when, for example, the onset or the demise of monsoonal precipitation is delayed or occurs prematurely. Such observational and modeling studies are needed to better understand the observed shrinkage of tropical glaciers and the projected associated changes in regional hydrology. Significant scientific progress is a prerequisite to adequately implement practical measures dealing with future changes in runoff behavior. Meaningful adaptation and mitigation plans can not be implemented without an adequate understanding of how climate affects glaciological and hydrological systems in the Cordillera Blanca today.

Acknowledgements

This study was supported by the National Science Foundation (EAR-0519415 awarded to MV) and by the Projects P16113 NO6 and P13567 GEO of the Austrian Science

Foundation (FWF) awarded to GK. Field work in Peru was carried out in cooperation with the Unidad de Glaciologia e Recursos Hidricos of INRENA, Huaraz, Peru. NCEP–NCAR reanalysis, OLR and GPCP data were obtained from the NOAA National Climatic Data Center (NCDC). CRU TS 2.1 data was received from the Tyndall Centre for Climate Change Research. We are grateful for the comments by Stefan Hastenrath and two anonymous reviewers, which helped to substantially improve this paper.

References

Adler, R.F., Huffmann, G.J., Chang, A., Ferraro, R., Xie, P.-P., Janowiak, J., Rudolf, B., Schneider, U., Curtis, S., Bolvin, D., Gruber, A., Susskind, J., Arkin, P., Nelkin, E., 2003. The version-2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979–present). J. Hydrometeor. 4, 1147–1167.

Ames, A., Dolores, S., Valverde, A., Evangelista, C., Javier, D., Ganwini, W., Zuniga, J., 1989. Glacier inventory of Peru, Part I. Hidrandina S.A. Huaraz, Peru.

Ames, A., Hastenrath, S., 1996. Mass balance and ice flow of the Urushraju glacier, Cordillera Blanca, Peru. Zeitschrift fuer Gletscherkunde und Glazialgeologie 32, 83–89.

Ames, A., 1998. A documentation of glacier tongue variations and lake development in the Cordillera Blanca, Peru. Zeitschrift fuer Gletscherkunde und Glazialgeologie 34 (1), 1–36.

Bradley, R.S., Keimig, F.T., Diaz, H.F., 2004. Projected temperature changes along the American Cordillera and the planned GCOS network. Geophys. Res. Lett. 31, L16210. doi:10.1029/2004GL020229.

Bradley, R.S., Vuille, M., Diaz, H.F., Vergara, W., 2006. Threats to water supplies in the Tropical Andes. Science 312, 1755–1756.

Chen, T.-C., Yoon, J.H., St. Croix, K.J., Takle, E.S., 2001. Suppressing impacts of the Amazonian deforestation by the global circulation change. Bull. Amer. Meteorol. Soc. 82, 2209–2216.

Costa, M.H., Foley, J.A., 1998. A comparison of precipitation datasets for the Amazon basin. Geophys. Res. Lett. 25 (2), 155–158.

Favier, V., Wagnon, P., Ribstein, P., 2004a. Glaciers of the outer and inner tropics: a different behavior but a common response to climatic forcing. Geophys. Res. Lett. 31, L16403. doi:10.1029/2004GL020654.

Favier, V., Wagnon, P., Chazarin, J.-P., Maisincho, L., Coudrain, A., 2004b. One-year measurements of surface heat budget on the ablation zone of Antizana glacier 15, Ecuadorian Andes. J. Geophys. Res. 109, D18105. doi:10.1029/2003JD004359.

Francou, B., Vuille, M., Wagnon, P., Mendoza, J., Sicart, J.E., 2003. Tropical climate change recorded by a glacier in the central Andes during the last decades of the 20th century: Chacaltaya, Bolivia, 16S. J. Geophys. Res. 108, D5, 4154. doi:10.1029/2002JD002959.

Francou, B., Vuille, M., Favier, V., Cáceres, B., 2004. New evidence for an ENSO impact on low latitude glaciers: Antizana 15, Andes of Ecuador, 0°28’S. J. Geophys. Res. 109, D18106. doi:10.1029/2003JD004484.

Garreaud, R.D., 1999. Multi-scale analysis of the summertime precipitation over the central Andes. Mon. Wea. Rev. 127, 901–921.

Garreaud, R., Aceituno, P., 2001. Interannual rainfall variability over the South American Altiplano. J. Climate 14, 2779–2789.

Garreaud, R., Vuille, M., Clement, A.C., 2003. The climate of the Altiplano: observed current conditions and mechanisms of past changes. Palaeogeogr. Palaeoclimatol. Palaeoecol. 194, 5–22.

Garreaud, R.D., Vuille, M., Compagnucci, R.H., Marengo, J., in press. Present-day South American climate. Palaeogeogr. Palaeoclimatol. Palaeoecol.

Georges, C., 2004. The 20th century glacier fluctuations in the tropical Cordillera Blanca, Peru. Arctic, Antarctic Alpine Res. 36 (1), 100–107.

Goddard, L., Graham, N.E., 1997. El Niño in the 90’s. J. Geophys. Res. 102 (C5), 10423–10436.

Hastenrath, S., Ames, A., 1995a. Recession of Yamarey glacier in Cordillera Blanca, Peru during the 20th century. J. Glaciol. 41 (137), 191–196.

Hastenrath, S., Ames, A., 1995b. Diagnosing the imbalance of Yanamarey glacier in the Cordillera Blanca of Peru. J. Geophys. Res. 100, 5105–5112.

Hastenrath, S., Polzin, D., Francou, B., 2004. Circulation variability reflected in ice core and lake records of the southern tropical Andes. Clim. Change 64, 361–375.

Jansson, P., Hock, R., Schneider, T., 2003. The concept of glacier storage: a review. J. Hydrol. 282, 116–129.

Juen, I., 2006. Glacier mass balance and runoff in the Cordillera Blanca, Perú. Ph.D. thesis, University of Innsbruck. 173 p.

Juen, I., Kaser, G., Georges, C., 2007. Modeling observed and future runoff from a glacierized tropical catchment (Cordillera Blanca, Perú). Global Planet. Change 59 (1–4), 37–48.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Amer. Meteorol. Soc. 77 (3), 437–471.

Kaser, G., Ames, A., Zamora, M., 1990. Glacier fluctuations and climate in the Cordillera Blanca, Peru. Ann. Glaciol. 14, 136–140.

Kaser, G., Georges, C., Ames, A., 1996a. Modern glacier fluctuations in the Huascaran–Chopicalqui-Massif of the Cordillera Blanca, Peru. Zeitschrift fuer Gletscherkunde und Glazialgeologie 32, 91–99.

Kaser, G., Hastenrath, S., Ames, A., 1996b. Mass balance profiles on tropical glaciers. Zeitschrift fuer Gletscherkunde und Glazialgeologie 32, 75–81.

Kaser, G., Georges, C., 1997. Changes of the equilibrium-line altitude in the tropical Cordillera Blanca, Peru, 1930–1950, and their spatial variations. Ann. Glaciol. 24, 344–349.

Kaser, G., Georges, C., 1999. On the mass balance of low latitude glaciers with particular consideration of the Peruvian Cordillera Blanca. Geograf. Ann. 81A (4), 643–651.

Kaser, G., 1999. A review of the modern fluctuations of tropical glaciers. Global Planet. Change 22, 93–103.

Kaser, G., Juen, I., Georges, C., Gomez, J., Tamayo, W., 2003. The impact of glaciers on the runoff and the reconstruction of mass balance history from hydrological data in the tropical Cordillera Blanca, Peru. J. Hydrol. 282 (1–4), 130–144.

Kaser, G., Georges, C., Juen, I., Mölg, T., 2005. Low-latitude glaciers: Unique global climate indicators and essential contributors to regional fresh water supply. A conceptual approach. In: Huber, U., Bugmann, H.K.M., Reasoner, M.A. (Eds.), Global Change and Mountain Regions: An overview of current knowledge, 23. Springer, Dordrecht, pp. 185–196.

Lemke, P., Ren, J., Alley, R.B., Allison, I., Carrasco, J., Flato, G., Fuji, Y., Kaser, G., Mote, P., Thomas, R.H., Zhang, T., 2007. Observations: changes in snow, ice and frozen ground. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Liebmann, B., Smith, C.A., 1996. Description of a complete (interpolated) outgoing longwave radiation dataset. Bull. Amer. Meteorol. Soc. 77 (6), 1275–1277.

Liebmann, B., Marengo, J.A., Glick, J.D., Kousky, V.E., Wainer, I.C., Massambani, O., 1998. A comparison of rainfall, outgoing longwave radiation and divergence over the Amazon basin. J. Climate 11, 2898–2909.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., Francis, R.C., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Amer. Meteorol. Soc. 78, 1069–1079.

Mark, B.G., Seltzer, G.O., 2003. Tropical glacier meltwater contribution to stream discharge: a case study in the Cordillera Blanca, Peru. J. Glaciol. 49 (165), 271–281.

Mark, B.G., Seltzer, G.O., 2005a. Evaluation of recent glacier recession in the Cordillera Blanca, Peru (AD 1962–1999): spatial distribution of mass loss and climatic forcing. Quat. Sci. Rev. 24, 2265–2280.

Mark, B.G., Seltzer, G.O., 2005b. Deglaciation in the Peruvian Andes: climatic forcing, hydrologic impact and comparative rates over time. In: Huber, U., Bugmann, H.K.M., Reasoner, M.A. (Eds.), Global Change and Mountain Regions: An overview of current knowledge, 23. Springer, Dordrecht, pp. 205–214.

Mark, B.G., McKenzie, J.M., Gomez, J., 2005. Hydrochemical evaluation of changing glacier meltwater contribution to stream discharge: Callejon de Huaylas, Peru. Hydrol. Sci. J. 50 (6), 975–987.

Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int. J. Climatol. 25, 693–712.

New, M., Hulme, M., Jones, P., 2000. Representing twentieth-century space-time climate variability. Part II: development of 1901–1996 monthly grids of terrestrial surface climate. J. Climate 13 , 2217–2238.

Peterson, T.C., Vose, R., Schmoyer, R., Razuvaev, V., 1998. Global Historical Climatology Network (GHCN) quality control of monthly temperature data. Int. J. Climatol. 18 (11), 1169–1179.

Raup, B., Racoviteanu, A., Khalsa, S.J.S., Helm, C., Armstrong, R., Arnaud, Y., 2007. The GLIMS geospatial glacier database: a new tool for studying glacier change. Global Planet. Change 56 (1–2), 101–110.

Sicart, J.E., Wagnon, P., Ribstein, P., 2005. Atmospheric controls of the heat balance of Zongo Glacier (16°S, Bolivia). J. Geophys. Res. 110, D12106. doi:10.1029/2004JD005732.

Silverio, W., Jaquet, J.-M., 2005. Glacial cover mapping (1987–1996) of the Cordillera Blanca (Peru) using satellite imagery. Rem. Sens. Environ. 95, 342–350.

Smith, T.M., Reynolds, R.W., 2004. Improved extended reconstruction of SST (1854–1997). J. Climate 17, 2466–2477.

Trenberth, K.E., Hoar, T.J., 1996. The 1990–1995 El Niño–Southern Oscillation event: longest on record. Geophys. Res. Lett. 23 (1), 57–60.

Trenberth, K., 1997. The definition of El Niño. Bull. Amer. Meteorol. Soc. 78 (12), 2771–2777.

Trenberth, K.E., Hoar, T.J., 1997. El Niño and climate change. Geophys. Res. Lett. 24 (23), 3057–3060.

Trenberth, K.E., Stepaniak, D.P., 2001. Indices of El Niño evolution. J. Climate 14, 1697–1701.

Vuille, M., Hardy, D.R., Braun, C., Keimig, F., Bradley, R.S., 1998. Atmospheric circulation anomalies associated with 1996/1997 summer precipitation events on Sajama ice cap, Bolivia. J. Geophys. Res. 103, 11191–11204.

Vuille, M., 1999. Atmospheric circulation over the Bolivian Altiplano during dry and wet periods and extreme phases of the Southern Oscillation. Int. J. Climatol. 19, 1579–1600.

Vuille, M., Bradley, R.S., Keimig, F., 2000a. Interannual climate variability in the Central Andes and its relation to tropical Pacific and Atlantic forcing. J. Geophys. Res. 105, 12,447–12,460.

Vuille, M., Bradley, R.S., Keimig, F., 2000b. Climate variability in the Andes of Ecuador and its relation to tropical Pacific and Atlantic sea surface temperatures anomalies. J. Climate 13, 2520–2535.

Vuille, M., Bradley, R.S., 2000. Mean annual temperature trends and their vertical structure in the tropical Andes. Geophys. Res. Lett. 27, 3885–3888.

Vuille, M., Bradley, R.S., Werner, M., Keimig, F., 2003. 20th century climate change in the tropical Andes: observations and model results. Clim. Change 59 (1–2), 75–99.

Vuille, M., Keimig, F., 2004. Interannual variability of summertime convective cloudiness and precipitation in the central Andes derived from ISCCP-B3 data. J. Climate 17, 3334–3348.

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B.G., Bradley, R.S., 2007. Climate change and tropical Andean glaciers — Past, present and future. Earth Sci. Rev., (submitted).

Wagnon, P., Ribstein, P., Francou, B., Pouyaud, B., 1999a. Annual cycle of energy balance of Zongo glacier, Cordillera Real, Bolivia. J. Geophys. Res. 104 (D4), 3907–3923.

Wagnon, P., Ribstein, P., Kaser, G., Berton, P., 1999b. Energy balance and runoff seasonality of a Bolivian glacier. Global Planet. Change 22, 49–58.

Wagnon, P., Ribstein, P., Francou, B., Sicart, J.E., 2001. Anomalous heat and mass budget of Glaciar Zongo, Bolivia, during the 1997–98 El Niño year. J. Glaciol. 47, 21–28.

Young, K.R., Lipton, J.K., 2006. Adaptive governance and climate change in the tropical highlands of western South America. Climatic Change 78, 63–102.

Yulaeva, E., Wallace, J.M., 1994. The signature of ENSO in global temperature and precipitation fields derived from the microwave sounding unit. J. Climate 7, 1719–1736.