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Tropical climate change recorded by a glacier in the central Andes during the last decades of the twentieth century: Chacaltaya, Bolivia, 16°S

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[1] The reasons for the accelerated glacier retreat observed since the early 1980s in the tropical Andes are analyzed based on the well-documented Chacaltaya glacier (Bolivia). Monthly mass balance measurements available over the entire 1991–2001 decade are interpreted in the light of a recent energy balance study performed on nearby Zongo glacier and further put into a larger-scale context by analyzing the relationship with ocean-atmosphere dynamics over the tropical Pacific-South American domain. The strong interannual variability observed in the mass balance is mainly dependent on variations in ablation rates during the austral summer months, in particular during DJF. Since high humidity levels during the summer allow melting to be distinctly predominant over sublimation, net all-wave radiation, via albedo and incoming long-wave radiation, is the main factor that governs ablation. Albedo depends on snowfall and a deficit during the transition period and in the core of the wet season (DJF) maintains low albedo surfaces of bare ice, which in turn leads to enhanced absorption of solar radiation and thus to increased melt rates. On a larger spatial scale, interannual glacier evolution is predominantly controlled by sea surface temperature anomalies (SSTA) in the eastern equatorial Pacific (Niño 1+2 region). The glacier mass balance is influenced by tropical Pacific SSTA primarily through changes in precipitation, which is significantly reduced during El Niño events. The more frequent occurrence of El Niño events and changes in the characteristics of its evolution, combined with an increase of near-surface temperature in the Andes, are identified as the main factors responsible for the accelerated retreat of Chacaltaya glacier. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1827 Hydrology: Glaciology (1863); 1863 Hydrology: Snow and ice (1827); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; *KEYWORDS:* tropical glaciers, ENSO, climate change, Andes, glacier mass balance, climate dynamics

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1. Introduction

[2] There is growing evidence that the observed glacier retreat in the tropical Andes has accelerated significantly since the early 1980s [e.g., *Brecher and Thompson*, 1993; *Ames and Francou*, 1995; *Hastenrath and Ames*, 1995a, 1995b; *Kaser*, 1999; *Francou et al.*, 2000; *Ramirez et al.*, 2001]. Recent studies indicate that this glacier recession coincides with a simultaneous increase in near-surface temperature and relative and specific humidity in the Andes [*Vuille and Bradley*, 2000; *Vuille et al.*, 2003]. Until recently, this large-scale climate change has not been linked to glacier evolution, primarily because monitored glaciers in the Andes were few and the available mass balance data are of rather poor temporal resolution. During the last decade however, several glaciers in Bolivia and Ecuador have been surveyed at a monthly resolution [*Francou et al.*, 1995, 2000] and now offer the possibility for a detailed study on the response of these glaciers to tropical climate change. In addition several years of energy balance measurements on glaciers in Bolivia have revealed the specific response and sensitivity of tropical glaciers to varying atmospheric conditions and documented the relative importance of the various energy fluxes at the glacier surface [*Wagnon et al.*, 1999a, 2001; *Sicart*, 2002].

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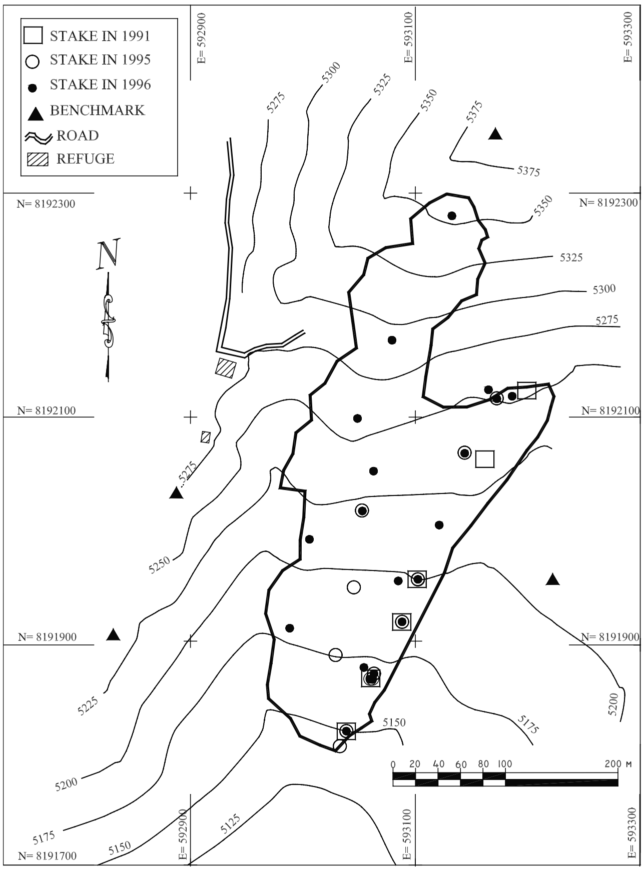


Figure 1. Map of Chacaltaya glacier in 1998, with location of the mass balance stakes in 1991, 1995 and 1996. North and east UTM coordinates in m. The observatory and rain gauges P6 and P7 mentioned in the text (not shown) are located outside the figure domain.

[3] Since small tropical glaciers are known to respond to climate signals at very short timescales, it seems reasonable to assume that their mass balance might reflect large-scale climate variability of the tropical troposphere. In this study, we present new data from the well-documented Chacaltaya glacier, representative of small Andean glaciers located in the outer tropics (Figure 1). Due to its small elevation range and its small size, the glacier is temperate and behaves alternatively as an ablation or an accumulation area. These conditions suggest that the glacier response to climatic variability is enhanced and detectable even at a short timescale. The aim of this study is thus to analyze the climate-mass balance relationship on both a microscale and a large scale, in order to improve our understanding of what caused the observed dramatic glacier retreat in this part of the world.

[4] In the next section we present the study area, give a short introduction to the climatic setting and briefly review previous similar studies. Section 3 includes an overview of the data and methods that were used, while section 4 presents the results of the mass balance study both in terms of its seasonal pattern and its evolution during the last decade. In section 5 we discuss the energy balance on Chacaltaya, while section 6 focuses on empirical climate-mass balance relationships on both a local and large scale. Section 7 ends with a summary and some concluding remarks.

2. Study Area, Previous Studies, and Climatic Setting

[5] Chacaltaya is a south facing glacier close to La Paz, Bolivia, extending in the year 2000 from 5140 m asl to 5360 m asl with a 0.06 km^2 surface area, representative of glaciers in the Cordillera Real, where 80% of the glaciers are <0.5 km^2 [*Francou et al.*, 2000] (Figure 1). The glacier has been continuously monitored for mass balance since September 1991 [*World Glacier Monitoring Service* (*WGMS*), 2001], and by means of a photogrammetric analysis of aerial photographs it was possible to reconstruct the glacier evolution over the last six decades [*Francou et al.*, 2000]. The recession rate was moderate from 1940 to 1963, with an average mass deficit of 0.22 m w.e. yr^{-1}, but it has increased in recent times from 0.57 m w.e. yr^{-1} (1963–1983) to 0.96 m w.e. yr^{-1} (1983–2000) [*Ramirez et al.*, 2001]. Due to this shrinkage, the ice thickness is reduced to less than 15 m and we can predict its complete disappearance within the next 10 years. 20 km to the northeast of Chacaltaya, Zongo, glacier has experienced the same interannual mass balance variability since 1991, but the greater size of the glacier (2.1 km^2) and its extensive area of accumulation, have helped to reduce the mass deficit to 25% of what was lost on Chacaltaya [*Ramirez et al.*, 2001].

[6] Since March 1996, energy balance measurements have been performed within the surface boundary layer of Zongo glacier, at 5150 m asl and at 5050 m asl, close to the mean equilibrium line altitude using automatic weather stations (AWS). These investigations have revealed the annual cycle of the surface energy balance of this glacier [*Wagnon et al.*, 1999a]. Moreover, comparing in detail the various terms of the energy balance between the La Niña year 1996–97 and the El Niño year 1997–98, has been useful to identify the local meteorological variables (increase in net all-wave radiation, related to lowered albedo through a precipitation deficit) responsible for the dramatic melting of Zongo glacier observed in 1997–98 [*Wagnon et al.*, 2001]. Although no similar energy balance measurements have been performed on nearby Chacaltaya, we focus on this glacier in the study at hand for several reasons: While mass balance on Zongo glacier was only measured on a relatively small section of the ablation zone (from 5170 to 5030 m asl), and not over the entire glacier, Chacaltaya is unique, in the sense that it is the only glacier where a monthly mass balance record exists, measured over an entire decade and covering the entire glacier. Furthermore, the small size of the glacier makes it particularly sensitive to climate fluctuations at short timescales, and thus a good choice to study mass balance-climate relationships. Finally, the close proximity of Chacaltaya to Zongo, where energy balance studies have been performed in great detail, allows the results to be transferred with reasonable accuracy.

[7] In the Bolivian Cordillera Real the year can be divided into three periods: the dry season (May–August) and the wet season (January–April) are separated by a transition period (September–December) where we observe a gradual buildup of the wet season with precipitation being

more and more frequent [*Sicart et al.*, 2002]. The climate in the Chacaltaya region is thus characterized by a distinct seasonality of precipitation. 90% (602 mm) of the annual precipitation amount (668mm) near Chacaltaya falls during austral summer, ONDJFMA, and more than 50% falls within the three main wet season months, DJF (average 1981–2001). Summer precipitation is associated with intense solar heating of the Altiplano surface, leading to a destabilization of the boundary layer, inducing deep convection and moist air advection from the eastern interior of the continent [*Vuille et al.*, 1998; *Garreaud*, 1999]. This moist air is typically released in afternoon and evening showers over the Altiplano [*Garreaud and Wallace*, 1997]. During the winter, dry conditions usually prevail over the Altiplano, associated with a strong zonal westerly flow. Even during the summer months, however, precipitation only occurs during periods with prevailing upper-air easterly winds, which allow near-surface moisture influx from the east and sustain deep convection over the Altiplano [*Garreaud*, 1999; *Vuille*, 1999]. In the upper troposphere an anticyclonic vortex, the Bolivian High, develops during the summer months. The positioning and the strength of this High are intrinsically linked to precipitation anomalies over the Altiplano, featuring an intensification and southward displacement of the High during wet episodes, while a weakening and northward displacement can be observed during dry periods [*Aceituno and Montecinos*, 1993; *Vuille et al.*, 1998; *Lenters and Cook*, 1999].

[8] On the interannual timescale, the Altiplano experiences similarly strong precipitation fluctuations, in particular during the austral summer wet season. Several studies have recently addressed this phenomenon and concluded that a significant fraction of this variability is related to the El Niño-Southern Oscillation (ENSO) phenomenon [*Aceituno*, 1988; *Vuille*, 1999; *Vuille et al.*, 2000; *Arnaud et al.*, 2001; *Garreaud and Aceituno*, 2001]. All studies concluded that El Niño years (warm phase of ENSO) tend to be dry, while La Niña years (ENSO cold phase) are often associated with wet conditions on the Altiplano. We will examine the influence of these ENSO-related climate anomalies on Chacaltaya glacier mass balance in section 6.2.

[9] Due to the scarcity of long and reliable time series of observational climate data from this region, very little is known about long-term trends, superimposed on this interannual variability. Recent studies based on observational and model data indicate that changes in precipitation amount and cloud cover over the last decades are rather minor in the tropical and subtropical Andes. Both variables are therefore considered to be unlikely candidates for explaining the observed recent retreat [*Vuille et al.*, 2003]. Near-surface temperature and humidity levels on the other hand have increased significantly throughout most of the tropical Andes. As shown by *Vuille and Bradley* [2000], temperature in the tropical Andes has increased by 0.10°–0.11°C decade^{-1} since 1939, and the rate of warming has more than tripled over the last 25 years (0.32°–0.34°C decade^{-1}). Similarly relative humidity has increased by 0.5–1.0% decade^{-1} between 1950 and 1995, and water vapor pressure has increased by 0.1–0.2 hPa decade^{-1} over the same time period. This is an important finding given the governing role of humidity in determining what fractions of the available energy are consumed by melting and sublimation processes respectively [*Wagnon et al.*, 1999a, 1999b].

3. Data and Methods

3.1. Mass Balance

[10] In September 1991, five PVC stakes were inserted into 10 m holes located below 5250 m asl on the east side of the glacier. This network was extended in 1995 with three stakes on the central axis, and in 1996, with five stakes along the western axis. Figure 1 represents all the stakes surveyed during the decade, including overlapping ones. With this configuration, the mass balance of each 25 m-elevation range, except for two zones (5300–5350 m) in the upper reach, has been measured by a minimum of one stake. Since the number of stakes increased in 1995 and 1996, we tested how representative of the entire glacier our pre-1996 measurements were by correlating the data obtained after 1996 with and without the new stakes included. The high coefficient of determination ($r^2 = 0.90$) confirms the homogeneity of the data set. Stakes were surveyed at the beginning of every month and snow depth, when present, was directly measured on several points inside a 1-m circle around the stakes. Snow density was generally only estimated because of its low variability. Snowfall events usually occur during relatively warm periods (temperature around 0°C); the snow becomes heavy as soon as it falls and the transformation of wet snow leads to a rapid increase in density to values close to 400 kg m^{-3}. However, when the glacier was covered by fresh snow, the snow density was measured in a minimum of two pits dug in two different elevation ranges. Monthly specific mass balance is calculated separately for each 25 m elevation range using the stake(s) within each range. Due to the fast decrease of the glacier surface elevation, a new topographic measurement was performed every year between September and December. The hydrological year in Bolivia lasts from September 1 to August 31. Thus, this study is based on a continuous and accurate series of monthly mass balance data for the complete 1991–2001 decade (120 months). A more detailed description of the mass balance program is given by *Ramirez et al.* [2001].

3.2. Meteorological Data

[11] Precipitation was measured at several locations surrounding the glacier (not shown in Figure 1). A rain gauge with a surface of 314 cm^2 has recorded precipitation every month since 1953 at the astronomical observatory (5240 m asl), in close proximity (500 m) of the glacier. The accuracy of the measurements seems to be reasonably good after 1980 but it was tested only for the recent years. Thanks to a new rain gauge with a 2000 cm^2 surface (named P6) installed in August 1991 at a distance of 2 meters from the former, data from the two precipitation series could be compared with each other between 1993 and 1997 (48 months). The high coefficient of determination ($r^2 = 0.89$) and the slope of the linear regression being close to 1 ($a = 0.97$), show that a good agreement exists between the two rain gauges. In addition, a good agreement was found between P6 and another rain gauge of the same type (P7) located at 5050 m asl close to the glacier snout. These tests

are necessary because precipitation at this elevation is exclusively solid and can vary widely according to sites.

[12] In addition to local climate data measured near or on the glacier, we used several additional climate data sets to study the impact of the large-scale circulation and climate aloft Chacaltaya on the glacier's mass balance between 1991 and 2001. Several key diagnostic variables (200 hPa geopotential height, 200 hPa meridional and zonal wind, and 500 hPa temperature) were extracted from the NCEP-NCAR reanalysis data set [*Kalnay et al.*, 1996] to assess the nature of the large-scale atmospheric forcing associated with a positive or negative mass balance on Chacaltaya. NOAA outgoing longwave radiation (OLR) data [*Liebmann and Smith*, 1996], available on a 2.5° latitude × 2.5° longitude grid, is a commonly used proxy for convective activity and precipitation in the tropics [e.g., *Liebmann et al.*, 1998], and was used as an additional diagnostic tool. These OLR data are a globally complete data set, measured at the top of the atmosphere by satellites and indicative of the energy emitted by the Earth's surface. In the presence of deep convective clouds, the satellite sensor measures radiation emitted from the top of the clouds, which are high in the atmosphere and thus cold, leading to low OLR values. In the case of clear sky conditions on the other hand, high OLR values represent radiation emitted from the Earth's surface and the lower atmosphere. These OLR data should thus not be confused with the outgoing longwave radiation $L\uparrow$, emitted from the glacier surface and measured locally within the boundary layer at 2 m above ground by a weather station, in order to assess the glacier's energy balance (see section 3.3). Finally the Global sea-Ice and Sea Surface Temperature (GISST 2.3b) data set was used to investigate the influence of tropical sea surface temperature anomalies (SSTA) on Chacaltaya mass balance, since tropical SST has been linked to rising temperatures and freezing levels in the Andes [*Diaz and Graham*, 1996; *Vuille et al.*, 2003].

3.3. Surface Energy Balance on Zongo Glacier (5150 m asl)

[13] Since some results of the energy balance investigations conducted on Zongo glacier [*Wagnon et al.*, 1999a, 1999b, 2001; *Sicart*, 2002] will be used here, we briefly describe the method used to calculate the energy fluxes. A detailed description is given by *Wagnon et al.* [1999a]. The local melting ΔQ_M at 5150 m asl is derived from the energy balance equation for a melting surface (fluxes toward the surface are positive) [e.g., *Oke*, 1987]:

$$R + H + LE + G + P = \Delta Q_M, \tag{1}$$

where R is net all-wave radiation, H is the turbulent sensible heat flux, LE is the turbulent latent heat flux, G is the conductive energy flux in the snow or ice, P is the heat supplied by precipitation, and ΔQ_M is the latent heat storage change due to melting or freezing. The net radiation is the balance of the incident and reflected short-wave radiation and the incoming and outgoing long-wave radiation:

$$R = S\downarrow - S\uparrow + L\downarrow - L\uparrow = S\downarrow(1 - a) + L\downarrow - L\uparrow, \tag{2}$$

where $S\downarrow$ is the incident short-wave radiation, $S\uparrow$ is the reflected short-wave radiation, α is the short-wave albedo of the snow surface, $L\downarrow$ is the incoming long-wave radiation, and $L\uparrow$ is the outgoing long-wave radiation. Since this glacier is isothermal at 0°C [*Francou et al.*, 1995], the annual conductive heat flux into snow or ice G is zero. Since precipitation is always snow in the vicinity of the equilibrium line and since snowfall intensities are usually weak, the heat supplied by precipitation P remains insignificant and negligible compared to the other terms of equation (1).

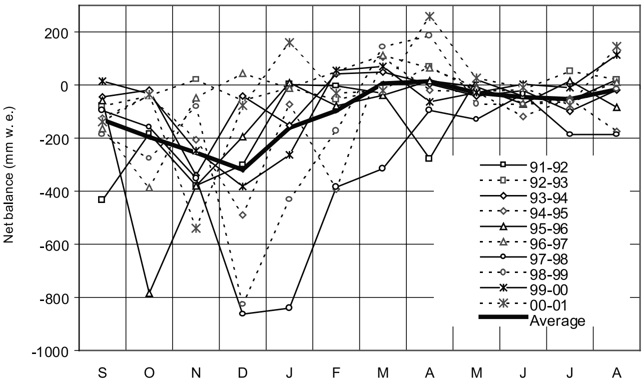


Figure 2. Chacaltaya's monthly mass balance between September and August (hydrologic year) from 1991 to 2001. Monthly means are shown by bold black line.

4. Chacaltaya Glacier Mass Balance During the 1991–2001 Decade

4.1. Seasonal Variations

[14] Figure 2 displays the 10 annual records of monthly mass balance measurements on Chacaltaya. Clearly there is a strong seasonality associated with mass balance variability; that is, the largest differences from year to year occur during the summer months October–April. During the dry and cold winter months May–September on the other hand, mass balance is always near the equilibrium and does not display any significant variations from year to year. Accordingly, the annual mass balance largely reflects the variability in summertime accumulation and ablation. This notion is confirmed by the strong correlation between the cumulative summer and annual mass balances ($r^2 = 0.98$, Figure 3). The largest fraction of year-to-year mass balance variability can be attributed to the three summer months DJF, which alone account for 78% of the total variance of the annual mass balance. As shown in Figure 2, negative mass balance is largest in December and January, which are the main wet season months. This implies that the accumulation and ablation seasons tend to coincide. This is consistent with results from previous studies, indicating that the annual mass balance of glaciers in Bolivia strongly depends on the starting date of the precipitation season, which generally occurs between December and February. At the same time this season is also characterized by a combination of factors which enhance melting processes at the glacier surface [*Wagnon et al.*, 1999a; *Sicart*, 2002].

4.2. Interannual Variations

[15] The dramatic cumulative loss of mass on this glacier over the decade (-1.3 m w.e. yr^{-1}) is superimposed on a

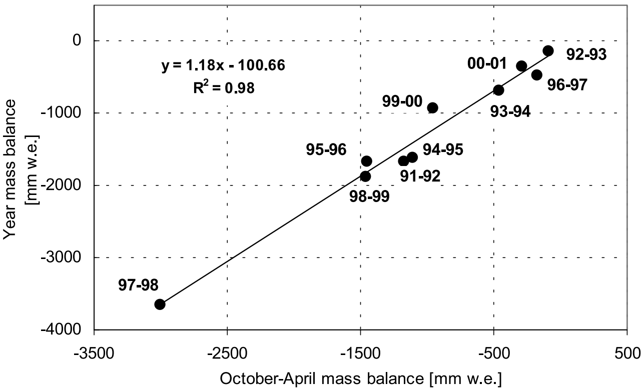


Figure 3. Summer (Oct.–April) mass balance versus annual mass balance. When the outlier (minimum value in 1997–98) is removed, the coefficient of determination is r^2 = 0.93 (n = 9).

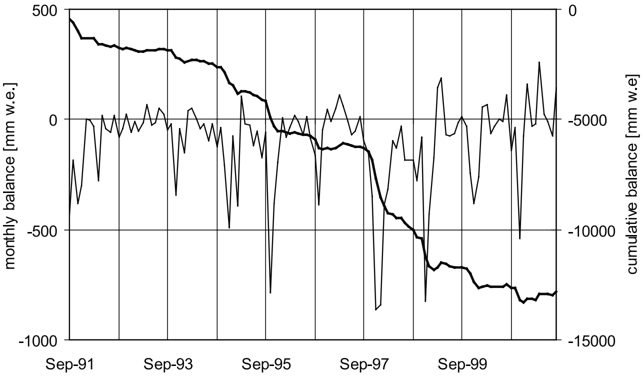


Figure 4. Monthly (thin line) and cumulative mass balance (thick line) on Chacaltaya glacier over the decade 1991–2001.

strong interannual variability (Figure 4). The highest ablation rates were concentrated within 3 periods, Sept. 1997–Feb. 1999, Sept. 1994–Dec. 1995 and Sept. 1991–April 1992 respectively. They are separated by three more moderate ablation periods, May 1992–Aug. 1994 (the only "near equilibrium" annual balance observed on the glacier), March 1999–Aug. 2001 and Jan. 1996–Aug. 1997. No period has impacted the mass balance trend in a way similar to 1997–1999, an exceptional 18-month period during which the glacier lost 6 m of water equivalent, i.e. 1/3 of the total ice volume. Figure 5 compares the cumulative mass balance on Chacaltaya (5350–5150 m asl) with the same time series from the upper ablation zone (5170–5030 m asl) of Zongo glacier [*Sicart*, 2002]. The mass balances of the two glaciers evolve in a similar fashion, implying a common response to the regional climate. The discrepancy in the overall mass loss (~7 m of w.e.) is largely due to the difference in elevation between the two investigated glacier zones.

5. Energy Fluxes at the Glacier Surface

[16] The observed mass balance variability presented in the previous section results from the energy balance at the glacier surface. Without measurements on Chacaltaya itself, however, we can only present a qualitative discussion based on the results obtained on Zongo Glacier [*Wagnon et al.*, 1999a, 1999b, 2001; *Sicart*, 2002]. First, the energy balance approach will bring a physical understanding of the seasonal evolution of the glacier mass balance and its interannual variability. Second, it will highlight the physical processes involved in the accelerated glacier retreat of the last decade.

5.1. Seasonal Evolution of the Mass Balance

[17] In section 4.1 we have observed that the end of the transition period and the first half of the wet season (ONDJFMA) and especially DJF, are the key months to explain the annual mass balance of the glacier, whereas the winter dry months are of little relevance. Various meteorological variables are involved in this seasonality:

1. During the summer months and especially during the wet season, the cloudiness is greatly enhanced, leading to increased incoming long-wave radiation $L\downarrow$. Since the outgoing long-wave radiation $L\uparrow$ remains almost unchanged throughout the year (melting conditions are encountered on Chacaltaya every day for several hours), the infrared radiative balance displays a pronounced seasonality, responsible for the seasonal evolution of the glacier melting (the averages of net infrared radiation for DJF and MJJA in 1999–2000 at 5050 m asl on Zongo Glacier are -12.6 W m^{-2} and -76.3 W m^{-2} respectively) [*Sicart*, 2002]. This sharp increase of the energy available at the glacier surface between MJJA and DJF corresponds to a theoretical excess melting of 500 mm w.e. per month if all this energy were used for fusion. Cloudiness is thus a very important meteorological variable controlling the seasonality of the melting at the glacier surface.

2. Another important variable is the albedo, which controls the net short-wave radiation. Due to the tropical location of Chacaltaya, the incident solar radiation $S\downarrow$ varies little throughout the year, and is even slightly lower during the cloudy summer months [e.g., *Hardy et al.*, 1998]. From September to December, there is no regular or heavy precipitation, the atmosphere is usually cloudless and low albedo bare ice is most of the time exposed at the

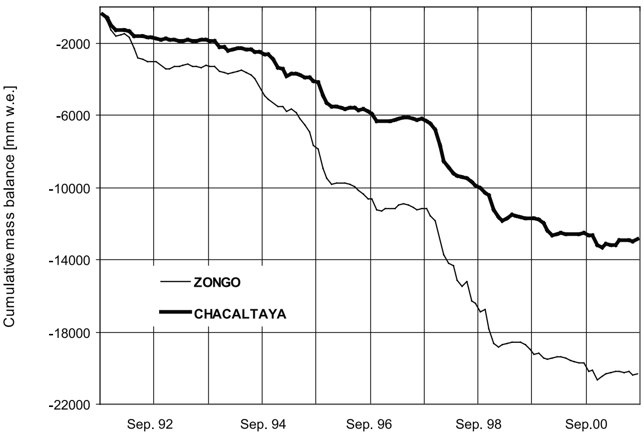


Figure 5. Cumulative mass balance of Zongo and Chacaltaya glaciers over the decade 1991–2001. Note that Zongo's data come from the upper ablation zone (5170–5030 m asl) [*Sicart*, 2002], while Chacaltaya's data cover the entire glacier (5360–5140 m asl).

glacier surface, leading to a strongly positive short-wave radiative balance. This net solar radiation of the south facing Chacaltaya glacier is increasing toward the summer solstice when the solar radiation $S\downarrow$ is maximum and the Sun is located to the south. Therefore, in November–December, the glacier experiences the highest melting rates of the year. During the precipitation season, due to frequent snowfalls, which cover the entire glacier, albedo remains high and net short-wave radiation drops. Nevertheless, melting is still high because of the increased incoming long-wave radiation $L\downarrow$. During the dry season, albedo slightly decreases from May to August when the snow cover of the wet season slowly disappears, and thus net short-wave radiation remains rather low until the end of August.

3. The dry season is characterized by low ablation rates related to the very negative long-wave radiative balance and to the strong latent heat flux. Indeed, due to the enhanced katabatic winds and low humidity of these dry winter months, the turbulent convection of the surface boundary layer, negligible during the wet season, is increased, leading to high sublimation (based on calculations on Zongo glacier, sublimation is assumed to be around 20–40 mm w.e. month^{-1} in MJJA). The energy used to sublimate snow is therefore no longer available for melting, which is a much more efficient ablation process than sublimation. Therefore, ablation is weak. Moreover, during clear nights of the dry season, which are characterized by a strongly imbalanced net long-wave radiation, the glacier surface is sometimes cooled down to $-15°$C. This nocturnal cooling of the surface layers of the glacier needs to be compensated in the morning, which again reduces the energy available for melting.

4. Precipitation, which is always solid on Chacaltaya, occurs mainly during the summer months and thus contributes to the seasonality of the glacier mass balance and its high variability during the summer months as well.

[18] In conclusion, on low latitude glaciers such as Zongo and Chacaltaya, characterized by an absence of major thermal seasonality, cloudiness, which controls the incoming long-wave radiation, precipitation, which has a strong feedback on albedo, and humidity, which is responsible for sublimation, are the key variables explaining the seasonal variation of the glacier mass balance.

5.2. Interannual Variability of the Mass Balance

[19] Since the glacier mass balance is mainly controlled by variations during the summer months, this period is key to explain the interannual mass balance variability. The summer months correspond to the wet season and therefore represent the time of year with largest interannual variations in the amount of accumulation, which is closely related to the glacier mass balance. Nonetheless, the feedback on albedo induced by precipitation is likely to be far more efficient in explaining the large variability of annual glacier mass balance than the annual variability of accumulation itself [*Wagnon et al.*, 2001]. Indeed, the annual mass balance of the glacier strongly depends on the starting date of the precipitation season, which ends a period of very intense melting around the summer solstice (December). For instance, heavy snowfall at the beginning of the wet season (DJ) will cover the glacier with a protective blanket of high albedo, thereby reducing the absorption of incident solar radiation and thus leaving little energy available for melt. On the other hand, if the precipitation season starts late, as is usually the case during El Niño years, the low-albedo bare ice of the transition period remains exposed at the surface for a longer time period and on a larger surface [*Wagnon et al.*, 2001; *Sicart*, 2002]. Therefore the absorption of short-wave radiation is greatly increased, sustaining high melt rates at the end of the transition season for a prolonged period of time. During the 1997/98 El Niño event for example, the maximum melt rate on Zongo Glacier was observed in February. In conclusion, precipitation is one of the most important meteorological controls for the annual mass balance; not only because it determines the amount of accumulation, but mainly because it controls albedo, which in turn is a key factor of the energy balance. The positive feedback of precipitation on albedo is all the more important since it occurs during the summer months when ablation is very efficient due to negligible sublimation and increased incoming long-wave radiation.

5.3. Mass Balance Evolution Over the Last Decades

[20] As shown by *Vuille and Bradley* [2000] and *Vuille et al.* [2003], the last 5 decades were characterized by a significant warming of roughly 0.1°C decade^{-1}, reaching more than 0.2°C decade^{-1} during the last 3 decades, and a simultaneous increase in water vapor pressure of 0.1–0.2 hPa decade^{-1}. Moreover, no significant change in precipitation or cloud amount during the humid season has been identified, and the Chacaltaya precipitation record also shows no significant trend during the two last decades, neither in the annual nor in the DJF precipitation amounts (not shown). It is thus tempting to link the mass balance changes of the Chacaltaya glacier to atmospheric temperature and humidity through the sensible and latent turbulent heat fluxes. Indeed, *Braithwaite* [1981] showed that air temperature is a useful parameter for the evaluation of melting on midlatitude glaciers, because the melting variability is controlled by the sensible heat flux (even if the main source of energy is the radiation). On Zongo glacier, however, the turbulent fluxes are to a first degree controlled by wind speed rather than air temperature or humidity [*Sicart*, 2002]. This is partly due to the thermally stable air column associated with high temperature and humidity levels, which reduces the turbulent exchanges. The sensible heat flux always remains small on tropical glaciers due to low thermal seasonality, low wind speed and low air density at very high altitude. The higher humidity should reduce sublimation, thus leaving more energy for melting. However, sublimation is only important during the dry season, whereas the annual mass balance mainly depends on the wet season when the air is always close to saturation. Thus, the dramatic loss of mass of the Chacaltaya glacier over the last decade is unlikely to be caused by turbulent heat fluxes.

[21] On the other hand it is quite plausible that the increase in air temperature and humidity during the last 2 decades led to enhanced incoming long-wave radiation, which in turn is responsible for the strong melt increase. *Ohmura* [2001] suggests that the air temperature information is transferred to the surface mainly through long-wave atmospheric radiation. This flux is generally the most important heat source for melting and comes from the

near-surface layer of the atmosphere (more than 70% from the first 1 km). In particular, the incoming long-wave radiation is directly related to the cloud amount, which plays a key role in the seasonality of the energy fluxes at the surface of tropical glaciers. However, since no meteorological measurements were conducted in the boundary layer of the Chacaltaya glacier, this discussion remains qualitative. Long series of meteorological measurements (several years), in and outside the boundary layer of the glacier, are necessary to assess the climatic causes of the interannual mass balance variability.

[22] Finally, it is important to keep in mind that the retreat of this glacier is accelerated once the glacier reaches a critical size, below which the edge effects cannot be neglected any more. Indeed, at the edge of a tropical glacier, the air temperature at the surface of surrounding rocks may exceed 20°C when solar radiation is maximal (Wagnon and Favier, measurements on Antizana Glacier, 0°30′S, 2002). Therefore, local advection of warm air above the glacier surface may sharply increase the sensible heat flux. In addition, the long-wave radiation emitted by the surrounding rocks toward the glacier greatly contributes to accelerate the melting [e.g., *Wendler*, 1974]. Chacaltaya has shrunk to its critical size and that is one reason why its mass deficit between 1991 and 2001 is far larger than that on Zongo (−12.8 m w.e. for Chacaltaya versus −2.7 m for Zongo). Another reason for the shrinkage is, of course, the absence of a permanent accumulation zone and thus the absence of mass transfer downstream. With an ELA generally lying above the upper reaches of the glacier, Chacaltaya has been reduced to an ablation zone during the last two decades.

6. Glacier-Climate Relationships

6.1. Mass Balance and Local Climate

[23] Based on the recent results by *Vuille and Bradley* [2000], which indicate a significant increase in the observed warming trend over the last 2–3 decades, we first investigate the simple linear relationship between monthly mass balance anomalies and NCEP-NCAR reanalyzed temperature anomalies at the 500 hPa level aloft Chacaltaya (average of four nearest grid cells). All significance levels are adjusted by taking into account serial correlation of the data [*Weatherhead et al.*, 1998]. If all months are considered, the correlation is significant at 0.05-level but the coefficient is low (r = −0.34). The correlation between the two variables increases slightly when only the summer months ONDJFMA are considered (r = −0.37). The best correlation, however, can be found between DJF mass balance and DJF temperature (r = −0.53). On interannual timescales a clear inverse relationship between mass balance and temperature becomes apparent (Figure 6), when the seasonal cycle is removed (r = −0.89). Near the equilibrium line, periods of negative (positive) mass balance values coincide with positive (negative) temperature anomalies. Over the entire decade, the periodicity of the oscillations has varied from one to two years. The dominant feature in the smoothed mass balance time series is the negative 1997–1999 event, which coincides with the strongest positive temperature anomaly (>1°C).

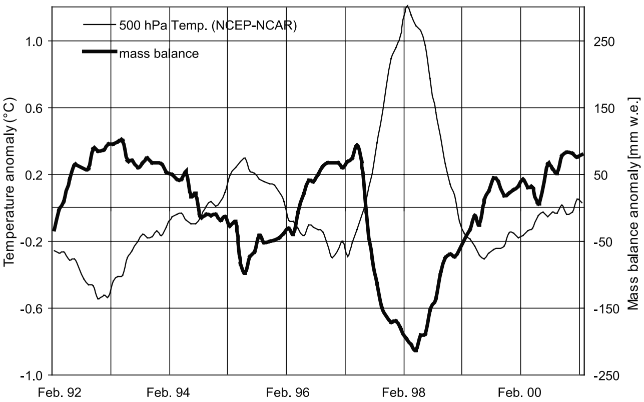


Figure 6. NCEP-NCAR 500 hPa temperature anomaly (averaged over 15°–17.5°S and 70°–67.5°W) and anomaly of Chacaltaya's mass balance from Sept. 1991 to Aug. 2001. Both time series have been smoothed with a 12-month-averaging filter. The means of temperature and mass balance are −5.8°C and −107 mm respectively.

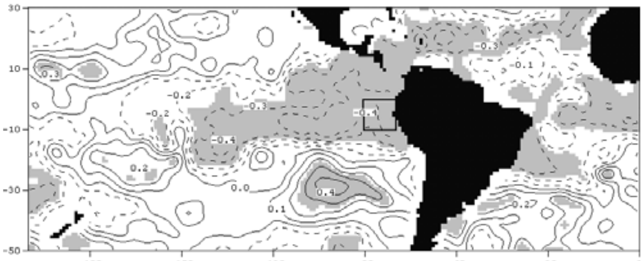
[24] Monthly precipitation and mass balance anomalies do not exhibit a significant correlation if all months are considered, but the correlation is significant at the 0.05 level during the summer months ONDJFMA (r = 0.27). Not surprisingly, the best correlation is again found for the main wet season months (r = 0.59 if only DJ are considered). Since the resolution of the Chacaltaya precipitation data is monthly, we cannot assess whether there has been a change in the onset date of precipitation, which would probably be most crucial for the glacier mass balance, because of the presence or lack of a protective blanket of fresh snow in the spring and its impact on the albedo. Daily or at least pentad data over long time periods would be necessary to answer this question.

[25] Since temperature and precipitation are strongly correlated on interannual timescales in the subtropical Andes [*Vuille et al.*, 2000], the relationship between either mass balance and precipitation or mass balance and temperature may be spurious and simply reflect the fact that wet and cold (dry and warm) summers tend to coincide. We thus performed a linear multiple regression analysis for the key-period DJF with monthly mass balance anomalies as dependent variable and precipitation (P) and temperature anomalies (T) as independent predictors. We performed a stepwise forward elimination procedure, where all variables, which explain a significant amount of variance in the presence of the other factors at the 95%-confidence level based on an F-test, are retained in the model. Our results indicate that both T and P explain a significant amount of variance (multiple r = 0.67). At the same time, however, such an attempt to explain mass balance variability based on local parameters alone is of quite limited diagnostic value, because it does not consider dynamical aspects and potential large-scale forcing mechanisms [*Sicart*, 2002].

6.2. Mass Balance and Large-Scale Forcing

[26] To link glacier mass balance with large-scale atmospheric dynamics allows for a more integrated view and discussion of the observed glacier retreat, because glaciers are receding throughout the tropical Andes in a very coherent way [*Kaser*, 1999; *Francou et al.*, 2000], and it is therefore reasonable to assume that this recession is

a) ONDJFMA corr. mass balance vs. SSTA



b) ASONDJF corr. mass balance vs. SSTA

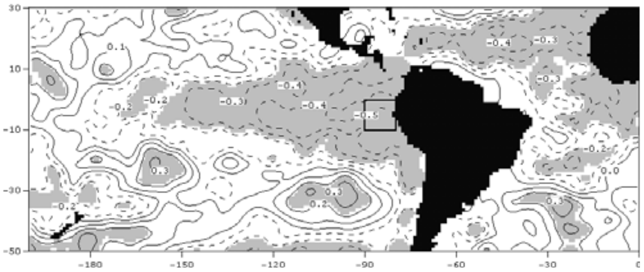


Figure 7. (a) Correlation map of monthly summer mass balance anomalies (ONDJFMA) on Chacaltaya glacier between 1991 and 2001 with contemporaneous tropical SSTA (GISST 2.3b); contour interval is 0.1; negative contours are dashed and regions where correlation is significant at the 95% level are shaded in gray. Black box indicates Niño 1+2 region (0°–10°S; 90°–80°W). (b) As in Figure 7a, but for correlation with ASONDJF SSTA (SSTA leads mass balance anomalies by 2 months).

associated with a large-scale climatic forcing, rather than caused solely by microclimatic effects. On interannual to interdecadal timescales the climate of the Altiplano region is linked to SSTA in the tropical Pacific [*Vuille et al*, 2000; *Garreaud and Aceituno*, 2001]. Summer precipitation on the Altiplano shows a very strong interannual variability, and there is clear evidence that a significant fraction of this variability is related to ENSO [e.g., *Francou and Pizarro*, 1985; *Aceituno*, 1988; *Lenters and Cook*, 1999; *Vuille*, 1999; *Vuille et al.*, 2000; *Arnaud et al.*, 2001; *Garreaud and Aceituno*, 2001; *Wagnon et al.*, 2001; *Garreaud et al.*, 2003]. All studies agree that La Niña years tend to be wet, while dry conditions usually prevail during El Niño years.

[27] In conjunction with dry conditions, the Altiplano also experiences above average temperatures during El Niño events. On average, near-surface summer temperatures are 0.7°–1.3°C higher during El Niño as compared to La Niña [*Vuille et al.*, 2000]. Tropical glaciers, such as Chacaltaya, thus do not only experience a deficit of summer precipitation and consequently reduced accumulation and a lowered albedo during El Niño events, but are also exposed to higher temperatures and an increase in incoming shortwave radiation due to reduced cloud cover. The consequences of such climatic conditions on the energy balance at the glacier surface have already been discussed in section 5.

[28] It is thus reasonable to assume that the accelerated retreat of the glacier is also related to the higher frequency and stronger intensity of El Niño events in recent decades. Indeed 1982–83 and 1997–98 represent the strongest events of the last century and the 1991–95 period experienced a quasi-permanent El Niño situation [*Trenberth and Hoar*, 1996]. These El Niño events were always marked by an important increase in air temperature and a deficit of precipitation, inducing a strong feedback on albedo [*Wagnon et al.*, 2001]. Therefore, during these El Niño years, glaciers experienced very negative annual mass balances, which have particularly accelerated their recession trend. In this context, the1992–93 year can be seen as a notable exception: although it formed part of the long El Niño phase 1991–95, this year was clearly cold, leading to the only (slightly) positive mass balance of the decade. This anomaly is probably related to the eruption of Mount Pinatubo in June 1991, which produced a large stratospheric cloud (the largest of the twentieth century), thereby significantly cooling the lower and midtroposphere throughout the tropics for several months [*Robock*, 2002].

[29] To illustrate the large-scale climatic forcing related to monthly accumulation and ablation on Chacaltaya and its connection with ENSO and Pacific climate variability, we regressed monthly mass balance anomalies from Chacaltaya during the summer months ONDJFMA from 1991 to 2001 upon NCEP-NCAR 200 hPa geopotential height and wind and 500 hPa temperature and interpolated OLR data. The correlation fields in Figures 7 and 8 thus portray atmospheric conditions under which mass balance is positive on Chacaltaya, while the fields are essentially reversed during times of a negative mass balance. Figure 7a reveals a negative correlation between tropical SSTA in the eastern equatorial Pacific and Chacaltaya mass balance, that is, the colder the SST off the coast of South America, the more positive the mass balance and vice versa. Indeed, the Chacaltaya mass balance between October and April is significantly correlated with SSTA in the Niño 1+2 region (0°–10°S; 90°–80°W, indicated by the black box in Figure 7) at the 95%-confidence level ($r = -0.43$). The highest correlation is achieved if a 2 month lag is introduced ($r = -0.50$), which indicates that the SSTA in the eastern tropical Pacific between August and February are the best predictor for ONDJFMA mass balance anomalies (Figure 7b). The percentage of explained variance is highest during the main accumulation and ablation months DJF (not shown), when mass balance anomalies are highly correlated ($r = -0.73$) with OND SSTA in the Niño 1+2 region.

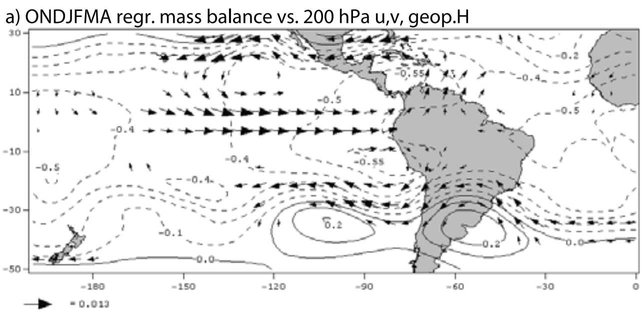
[30] The correlation of ONDJFMA mass balance anomalies with contemporaneous 200 hPa geopotential height anomalies (Figure 8a) indicates that a more positive mass balance on Chacaltaya is associated with a colder tropical troposphere and thus a weaker meridional temperature gradient in the subtropics (reduced meridional baroclinicity). The wind field in Figure 8a displays the regression coefficient between standardized mass balance anomalies and the local wind field at each grid point. This regression map is thus indicative of the strength (in m s^{-1}), sign and significance of local anomalies at each grid point associated with a unit anomaly of the mass balance time series. Clearly, easterly wind anomalies prevail over the central Andes during periods of positive mass balance anomalies (Figure 8a), which is consistent with the notion of enhanced precipitation and snow accumulation during periods of easterly wind anomalies [*Vuille*, 1999; *Vuille et al.*, 2000; *Garreaud and Aceituno*, 2001; *Garreaud et al.*,

2003; S. Hastenrath et al., Circulation variability reflected in ice core and lake records of the southern tropical Andes, submitted to *Climate Change,* 2003].

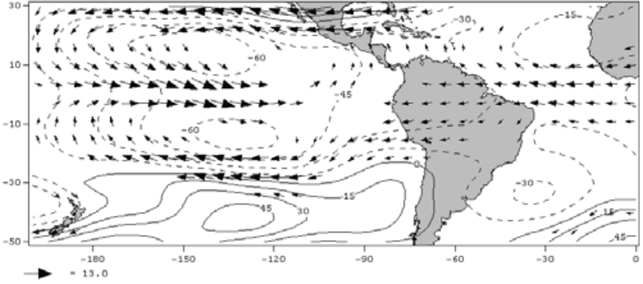
[31] The correlation field between mass balance and NCEP-NCAR-500 hPa temperature anomalies (Figure 8c), indicates a close negative association between mass balance and atmospheric temperature throughout the tropical Andes and the eastern Pacific and is consistent with the cold characteristics of the midtroposphere during periods of positive mass balance anomalies displayed in Figure 6. However, as mentioned before, this does not necessarily imply that ablation is lower during Pacific cold events because of lowered temperature (i.e., reduced melting), but might merely reflect the close correlation between tropical SSTA, precipitation and temperature in the tropical Andes on interannual timescales. This hypothesis is further supported by the OLR correlation field (Figure 8c), indicating that mass balance on Chacaltaya is also closely negatively related to regional anomalies in outgoing longwave radiation; that is, mass balance is more positive (negative) when convective activity and precipitation are enhanced (subdued).

[32] The large-scale pattern of OLR, 200 hPa geopotential height and wind field over the Pacific-South American domain is reminiscent of the canonical ENSO mode [e.g., *Kousky and Kayano*, 1994; *Yulaeva and Wallace*, 1994]. Further support for this notion stems from a composite analysis where we calculated the difference between La Niña and El Niño episodes during ONDJFMA between 1991 and 2001 for the same variables (Figures 8b and 8d). El Niño (La Niña) phases used in these composites are based on a definition similar to the one by *Trenberth* [1997], but we used the Niño 1+2− instead of the Niño3.4-index and a slightly different reference period (1951−80 instead of 1950−79) to compute the monthly anomalies. An El Niño (La Niña) event thus occurred if the 5-month running mean of SSTA in the Niño 1+2 region exceeded (or remained below) 0.4°C (−0.4°C) for at least 6 consecutive months. The geopotential height pattern in Figure 8b exhibits negative anomalies throughout the tropics, symmetrical about the equator, and positive anomalies in the southern midlatitudes, resulting in a reduced meridional temperature gradient along much of the subtropics near 30°S, typical of the tropical troposphere during a strong La Niña event. The resulting wind field is dominated by upper-air equatorial westerlies and a weakened subtropical jet

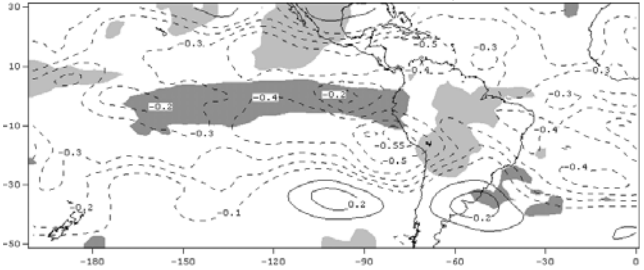
a) ONDJFMA regr. mass balance vs. 200 hPa u,v, geop.H



b) ONDJFMA WARM-COLD 200 hpa u,v, geop.H.



c) ONDJFMA corr. mass balance vs. OLR, 500 hPa temp.



d) ONDJFMA WARM-COLD OLR, 500 hPa temp.

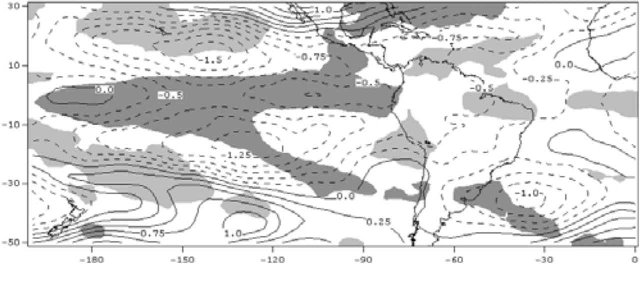


Figure 8. (opposite) (a) Correlation map of monthly summer mass balance anomalies (ONDJFMA) on Chacaltaya glacier between 1991 and 2001 with contemporaneous 200 hPa geopotential height and regression map with 200 hPa wind anomalies from NCEP-NCAR reanalysis. Contour interval for geopotential height correlation is 0.1 and 0.05 for values <−0.50; negative contours are dashed. Wind field is only plotted where either zonal or meridional component is significantly correlated at the 95% confidence level based on Student's t-test. Scale for wind vector (m s^{-1}) is given in lower left. (b) Composite difference (La Niña - El Niño) of 200 hPa NCEP-NCAR wind field and geopotential height for ONDJFMA between 1991 and 2001. Contour interval is 15 gpm and negative contours are dashed. Scale for wind vector (in m s^{-1}) is given in lower left. Wind vectors are only plotted if either zonal or meridional component is significantly different between La Niña and El Niño episodes, based on two-tailed Student's t-test. For definition of La Niña and El Niño events, see text. (c) As in Figure 8a, but for correlation with OLR and 500 hPa NCEP-NCAR temperature anomalies. OLR field is only plotted where correlation is significantly positive (dark gray) or negative (light gray) at the 95% level respectively. Contour interval for temperature correlation is 0.1 and 0.05 for values <−0.50; negative contours are dashed. (d) As in Figure 8b, but for OLR and 500 hPa temperature. OLR field is only plotted in light (dark) gray over regions where values are significantly lower (higher) during La Niña as compared to El Niño at the 95% level respectively, based on a two-tailed Student's t-test. Contour interval for temperature field is 0.25°C, and negative contours are dashed.

(enhanced easterly anomalies). The 500 hPa temperature field (Figure 8d) shows the typical features associated with ENSO, that is, a La Niña-related cooling throughout the tropical midtroposphere and the distinctive "dumbbell pattern" [*Yulaeva and Wallace*, 1994] with negative anomalies centered near 130°W at 15°N and 15°S. The OLR composite (Figure 8d) also shows the well known anomalies related to ENSO [e.g., *Kousky and Kayano*, 1994] with increased (decreased) convection during La Niña (El Niño) over NE-Brazil and the central Andes, while the opposite pattern emerges over the central equatorial Pacific.

[33] All these features are reproduced to some extent in the correlation field of Chacaltaya mass balance (Figures 8a and 8c), providing evidence for a dominant tropical Pacific control on the mass balance of this glacier. The causal mechanism linking tropical SSTA with glacier mass balance in the Andes is thus the same as described previously for precipitation [*Garreaud and Aceituno*, 2001; *Garreaud et al.*, 2003]. Wet summers on the Altiplano are associated with a La Niña related cooling of the tropical Pacific, a colder tropical troposphere, and thus enhanced easterly (weakened westerly) flow over the Altiplano as a response to the reduced meridional baroclinicity at subtropical latitudes. This easterly flow over the Andes, through downward mixing of momentum [*Garreaud*, 1999], enhances moisture advection in near-surface levels from the continental lowlands (Amazon basin) to the east and thus leads to wet conditions on the Altiplano. During dry summers (El Niño conditions) the pattern is essentially reversed. This result is of great importance because it shows that (1) glacier mass balance is linked to SSTA in the tropical Pacific and (2) that this linkage is being translated through changes in precipitation. It follows that mass balance anomalies on Chacaltaya are largely governed by climatic conditions in the tropical Pacific domain. This is consistent with observations that indicate an accelerated negative mass balance and glacier retreat in many tropical Andean locations after the mid 1970s, concurrent with the 1976/77 Pacific climate shift [e.g., *Ebbesmeyer et al.*, 1991]. Indeed, SSTA in the Niño 1+2 region have been consistently higher during the ASONDJF season since this shift took place. The higher SST off the coast of South America during this time of the year do not necessarily reflect a general rising trend but are rather associated with the change in the evolution of ENSO. Before 1976/77, El Niño events usually developed along the west coast of South America and then spread westward, but after the Pacific climate shift this evolution changed, and ENSO events now tend to first develop in the central equatorial Pacific and then spread westward [*Trenberth and Stepaniak*, 2001]. As a result, SST during ASONDJF, crucial for the Chacaltaya mass balance, have been consistently higher since 1976/77. Figure 9 show this relationship based on subdecadal to multidecadal averages of Chacaltaya mass balance and Niño 1+2 SSTA during ASONDJF. The dependence of Chacaltaya mass balance on eastern equatorial SSTA on quasi-decadal timescales is quite evident, although some time intervals used in this exercise overlap and their length varies, due to the limited information available before 1991. Based on this simple linear relationship, a sustained SSTA of −0.24°C (as compared to the 1951–80 average) would be required during ASONDJF in the Niño 1+2 region in order to equilibrate mass balance on Chacaltaya. This estimate indicates that Chacaltaya glacier is completely out of balance with modern climate.

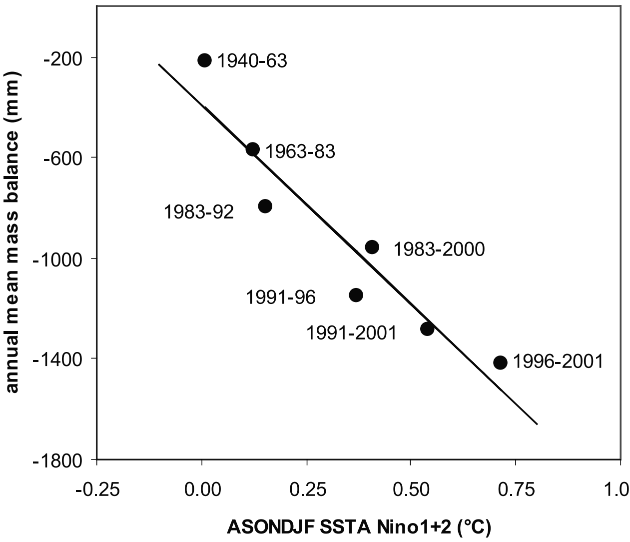


Figure 9. Linear relationship between subdecadal to multidecadal averages of Chacaltaya mass balance and ASONDJF SSTA in the Niño 1+2 region. SSTA are based on 1951–80 average; mass balance values are averages of annual totals (Oct.–Sept.). Note that time intervals overlap and their length varies. Mass balance data before 1991 are from *Francou et al.* [2000].

7. Summary and Conclusion

[34] Accurate mass balance measurements conducted on a monthly basis over the last decade made it possible to analyze the response of Chacaltaya glacier to recent climate change in great detail. An energy balance study, performed on the nearby Zongo glacier enabled us to understand the processes responsible for the ablation on the glacier surface. Finally the influence of the large-scale circulation and tropical SST on Chacaltaya mass balance was investigated. As principal results, we point out the following:

1. The glacier mass balance is closely related to atmospheric conditions during the austral summer months October–April, in particular during December–February.
2. At this time of year (ONDJFMA), humidity levels are high, and therefore melting predominates over sublimation. Net all-wave radiation, via albedo and incoming long-wave radiation, is the dominant factor which governs ablation. Albedo depends on precipitation, which is always solid at this elevation. A deficit of precipitation at the end of the transition period and in the core of the wet season (DJF) delays the installation of the fresh snow cover and maintains the low albedo bare ice in contact with the atmosphere late during the summer, leading to an enhanced absorption of solar radiation and thus, to increased melting. At the same time such a situation is associated with reduced cloudiness, which increases the amount of incoming solar radiation received at the glacier surface, an effect that is enhanced on the south-oriented Chacaltaya glacier.
3. There is a strong correlation between mass balance and reanalyzed temperature on interannual timescales.

Temperature, however, is not the main variable in the energy balance, which could explain melting, particularly not on short timescales (days and months). Other factors play a more important role, in particular humidity, which governs sublimation; precipitation, whose variability, particularly during DJF, induces a positive feedback on albedo; and cloudiness, which controls the incoming long-wave radiation. Nevertheless, all these meteorological variables are strongly interconnected, and especially air temperature is related to humidity and cloudiness. Since temperature integrates all the fluxes, it appears to be significantly correlated with mass balance on longer timescales (years). Therefore, air temperature remains a relevant variable to explain glacier mass balance evolution and is a good indicator for climate change, which might affect long-term mass balance trends. However, we emphasize that the apparent correlation between temperature and mass balance does not reflect the real physical processes present at the glacier surface.

4. Glacier evolution is controlled to a large part by tropical Pacific SSTA. During the ENSO warm phases (El Niño), precipitation is less abundant, and dry periods occur more frequently during the summer. This situation increases incoming solar radiation, reduces snow accumulation and decreases albedo on the glacier surface. Air temperature also increases during El Niño. During the relatively wet and cold La Niña periods, opposite conditions prevail, which can lead to a near-equilibrium mass balance. The large-scale linkage between higher SST in the tropical Pacific and local mass balance (translated through a precipitation deficit and related changes in cloudiness, albedo and incoming short- and longwave radiation) is through enhanced meridional baroclinicity at midlatitudes, which leads to weaker easterly winds and reduced moisture influx from the continental lowlands.

5. The best predictor for Chacaltaya mass balance is SST in the Niño 1+2 region during the spring and early summer, August to February (2-month lead). The higher SST off the coast of South America observed during this time of the year since the Pacific climate shift 1976/77, most likely contributed to the accelerated glacier retreat on Chacaltaya. A simple linear regression estimate indicates that sustained SSTA of $-0.24°C$ (as compared to the 1951–80 average) would be required during ASONDJF in the Niño 1+2 region in order to equilibrate mass balance on Chacaltaya.

6. Discrete, large-scale atmospheric events, such as the Pinatubo eruption of June 1991, are recorded by the glacier. During several months, the cooling effect of the volcanic aerosols interrupted the long 1990–1995 El Niño period, causing the only slightly positive mass balance observed over the entire decade on this glacier.

[35] In conclusion, this study suggests that the Chacaltaya glacier directly reflects climate change in the tropical Pacific-South American domain. The noise induced by the local conditions-size, aspect and exposure to the principal fluxes-is of minor importance, although it will increase as edge effects become more dominant due to the smaller glacier size. As most of the glaciers in the outer tropical Andes, Chacaltaya accelerated its recession since the early 1980s in response to important changes in the tropical Pacific domain. A temperature increase of more than 0.5°C in 30 years, together with higher humidity levels, is consistent with the increased melt rates observed during this period. Precipitation does not show a significant trend over the last decades, but the negative anomalies systematically recorded during the warm ENSO phases have provoked a positive feedback with solar radiation and temperature, enhancing melt processes. The higher frequency and the changed spatiotemporal evolution of El Niño since the mid 1970s, together with a generally warming troposphere over the tropical Andes, explains the recent dramatic shrinkage of glaciers in this part of the world.

[36] **Acknowledgments.** NCEP-NCAR reanalysis and interpolated OLR data were obtained from the NOAA Climate Diagnostics Center. Thanks to Robert Gallaire (IRD, La Paz) and Edson Ramirez (IHH, La Paz) for their help in the data collection and to Frank Keimig for a careful review. Three anonymous reviewers provided helpful comments that resulted in a significant improvement of this manuscript.

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