RECENT GLACIER RETREAT AND CLIMATE TRENDS IN CORDILLERA HUAYTAPALLANA, PERU

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ABSTRACT

We analyzed 19 annual Landsat Thematic Mapper images from 1984 to 2011 to determine changes of the glaciated surface and snow line elevation in six mountain areas of the Cordillera Huaytapallana range in Peru. In contrast to other Peruvian mountains, glacier retreat in these mountains has been poorly documented, even though this is a heavily glaciated area. These glaciers are the main source of water for the surrounding lowlands, and melting of these glaciers has triggered several outburst floods. During the 28-year study period, there was a 55% decrease in the surface covered by glaciers and the snowline moved upward in different regions by 93 to 157 meters. Moreover, several new lakes formed in the recently deglaciated areas. There was an increase in precipitation during the wet season (October-April) over the 28-year study period. The significant increase in maximum temperatures may be related to the significant glacier retreat in the study area. There were significant differences in the wet season temperatures during El Niño (warmer) and La Niña (colder) years. Although La Niña years were generally more humid than El Niño years, these differences were not statistically significant. Thus, glaciers tended to retreat at a high rate during El Niño years, but tended to be stable or increase during La Niña years, although there were some notable deviations from this general pattern. Climate simulations for 2021 to 2050, based on the most optimistic assumptions of greenhouse gas concentrations, forecast a continuation of climate warming at the same rate as documented here. Such

changes in temperature might lead to a critical situation for the glaciers of the Cordillera Huaytapallana, and may significantly impact the water resources, ecology, and natural hazards of the surrounding areas.

Keywords: Glacier retreat, snow line, climate change, lake formation, Cordillera Huaytapallana, Peru.

1. Introduction

The central Andes have 99% of the tropical glaciers world-wide and 71% of these glaciers are in Peru (Vuille et al., 2008; Chevalier et al., 2011). Glaciers are the major source of freshwater for some of the largest cities of South America, including Quito, Lima, and La Paz. These glaciers also provide water for irrigation of traditional agriculture in the mountains, modern intensive farming in the foothills and lowlands (Messerli, 2001; Mark, 2008; Bury et al., 2011), and hydropower (Vergara et al., 2007; Chevalier et al., 2011). However, glaciers are also behind natural hazards and have caused thousands of fatalities in recent decades. Glacial lakes may overflow, chunks of glaciers may collapse into lakes, and high seismic activity can increase the risk of glacial lake outburst floods (GLOFs). These can lead to flooding of croplands and residential areas in the alluvial fans and valley bottoms (Reynolds, 1992; Portocarrero, 1995; Carey, 2005; Carey et al., 2012).

There has been a marked decrease in the glaciated areas of the Peruvian Andes since the end of the Little Ice Age in ~1850 (Georges, 2004; Vuille et al., 2008), and an acceleration in the degradation and retreat of these glaciers in the last decades of the 20th century (Kaser, 1999; Francou and Vincent, 2007; Raup et al., 2007). Thus, from 1970 to 1997, glacier coverage in Peru declined by more than 20% (Bury et al., 2011; Fraser, 2012). This recent accelerated decline is associated with an increase in air

temperature across the region (Kaser and Osmaston 2002; Vuille and Bradley, 2000; Mark and Seltzer, 2005; Bradley et al., 2009). Higher air temperatures increase heat transfer and the portion of precipitation in the liquid phase; but an increase in temperature also raises the saturation vapor pressure, causing a rise in specific humidity under the assumption of constant relative humidity (Hense et al., 1988; Wagnon et al., 1999). The reduced latent heat flux limits sublimation, and available radiative energy is more efficiently consumed by melting, leading to increased loss of glacier mass (Sicart et al., 2005). The retreat of these glaciers has led to the formation of new proglacier lakes and an increase in the surface and volume of many existing lakes (Ames, 1998). It has also increased the risk of avalanches, glacier collapses (Fraser, 2012), and flooding during the wet season because more rain reduces the buffering effect of ice and snow (Peduzzi et al., 2010). Moreover, glacier retreat has also increased discharges from glacier-fed streams. When glacial replenishment of these streams ceases, there will be reduced dry-season flows and increased hydrologic variability (Mark and Seltzer, 2005; Juen et al., 2007; Bury et al., 2011).

In view of the environmental and socioeconomic significance of the Andean glaciers, many previous studies have examined the general characteristics, significance, and changes of Peruvian glaciers (see the reviews of Vuille, 2008a and Rabatel et al., 2013 as an example). However, most of this research has focused on the Cordillera Blanca, because it is the largest glacier-covered area of the tropical Andes, and has a long record of natural hazards, and outburst floods and avalanches in this region have killed 25,000 people in the Callejón de Huaylash since 1940 (Portocarrero, 1995; Fraser, 2012). There have been studies of some other mountainous regions of Peru, including the Cordillera Huayhuash, Cordillera Raura (McFadden et al., 2011), Cordillera Vilcanota (Brecher and Thompson, 1993; Thompson et al., 2006; Seimon et

al., 2007; Salzmann et al., 2013), and Coropuna (Racoviteanu et al., 2007). However, the changes of some heavily glaciated mountain regions in Peru have not yet been studied in detail. One example is the Cordillera Huaytapallana (Province of Junin, Central Peru), which has many mountains exceeding 5000 m a.s.l. and numerous glaciers that are the main source of freshwater for domestic and agricultural uses in the Mantaró River Basin, which has more than 1,000,000 inhabitants (ANA, 2010). This region also has a history of seismic activity associated with the Huaytapallana fault (Dorbath et al, 1991). Moreover, glacial lake outburst floods (GLOFs) have occurred here in recent decades because of the accelerated melting of glaciers. For example, a GLOF occurred in the Shulcas River in December of 1990 and it destroyed hundreds of houses and caused many fatalities in the city of Huancayo. In the last decade, the Geophysical Institute of Peru (IGP) has analyzed the hydrological significance of some headwaters to determine how climate change may impact future water availability in this region (IGP, 2010; Arroyo, 2011). Zubieta and Lagos (2010) examined ten Landsat TM images to estimate changes in ice cover over the most glaciated area of the Mantaro river basin and concluded that this lost 59% of its ice cover from 1974 to 2006.

In the present study, we analyzed changes in the glaciated areas and in the mean elevation of the snowline (limit between snow and ice in a glacier that roughly separates the accumulation and ablation zones) from 1984 to 2011 for the entire Cordillera Huaytapallana, a region that includes six glaciated areas. We also studied the relationship of changes in glaciers with local changes in temperature and precipitation and variability of the El Niño/La Niña Southern Oscillation (ENSO), which previous studies identified as the main source of interannual climate variability and changes in the annual mass of glaciers in other Peruvian mountains (Kaser et al., 2003; Vuille et al., 2008a; Rabatel et al., 2013). Finally, we used temperature and precipitation

projections simulated by different climate models to forecast changes of glaciers of this region from 2021 to 2050.

2. Study

The Cordillera Huaytapallana is in the eastern part of the Central Andes of Peru, north of the city of Huancayo (Figure 1). The Cordillera drains into the Mantaró and Perene rivers, which are part of the Amazon basin. The study area includes the main mountain area, Huaytapallana, and other five neighboring glaciated mountains: Pitita, Marairazo, Utcohuarco, Azulcocha, and Chapico. The Huaytapallana area contains 30 peaks from 4850 m a.s.l. to 5572 m a.s.l (the height of Huaytapallana, also known as Lazuntay), and is heavily glaciated. The Chapico and Utcohuarco areas (east of the Huaytapallana area) also have significant glaciers, and the maximum elevations in these areas exceed 5300 and 5150 m a.s.l., respectively. The presence of glaciers in the other three areas (north of the Huaytapallana area) is very limited and maximum elevations are close to 5000 m a.s.l. in all three areas. Glaciers in Cordillera Huaytapallana are typically of the cirque type and many are hanging glaciers and heavily crevassed because of the steepness. This region also has numerous lakes, many of which formed in recent decades due to the rapid glacier retreat in this area.

Figure 2 shows the long-term monthly precipitation and temperature at two locations close to the Cordillera. These regions exhibit climatic conditions typical of tropical mountains, with a wet season from October to April and a dry season from May to September. The dry season only receives about 10% of the annual precipitation. Due to the proximity of this region to the equator ($\sim 11^{\circ}\text{S}$ latitude), the temperature (especially the maxima) has very low annual variability. The minimum temperature has moderate annual variability, and July is the coldest month. At 4475 m a.s.l. (Tunelcero

observatory), the minimum temperature is below freezing during the dry season, but the mean maximum temperature exceeds 10° C throughout the year.

Despite the low annual variability in temperature, Sicart et al. (2005) showed that the energy balance of glaciers in the outer tropics is characterized by marked seasonality of incoming long-wave length radiation because of increased cloud cover during the wet season. The dry season is characterized by low ablation because of the very negative long-wavelength radiative balance and the strong latent heat flux. Indeed, due to the high katabatic winds and low humidity of the dry winter months, turbulent convection of the surface boundary layer, which is negligible during the wet season, is increased and this leads to high sublimation (Francou et al., 2003).

3. Data and Methods

3.1. Processing of remote sensing data

We reviewed all available Landsat-Thematic Mapper (TM) and -Enhanced Thematic Mapper (ETM+) images from the archives of the United States Geological Survey (USGS, <http://landsat.usgs.gov/>). Most studies based on Landsat data consider ETM+ and TM radiometry to be comparable, so we used TM data from 1984 and, switched to ETM+ data when it became available because of the better calibration of this sensor (Teillet et al., 2001). We switched back to TM due to the ETM+ SLC failure in 2003. A total of 19 images were processed for analysis of ice-covered areas and the locations of snowlines for the period of 1984 to 2011. The images were taken during the dry season (June-August) because of the low cloud cover and minimal snow cover during that season. This reduces misclassification of ice-covered areas and provides a better classification of the snowlines. For some years, it was not possible to select an

image because the presence of a significant cloud cover or anomalous snow accumulation prevented discrimination of glaciated surfaces from seasonal snow cover.

Images provided by the USGS were processed to Standard Terrain Correction (level 1T), which provides systematic radiometric and geometric accuracy by incorporating ground control points while employing a Digital Elevation Model (DEM) for topographic accuracy (more details in http://landsat.usgs.gov/Landsat_Processing_Details.php). Geodetic accuracy of the product depends on the accuracy of the ground control points and resolution of the DEM (30 m cell size). The X and Y root mean square error was less than 30 m (1 pixel) for all images and provided a precise geometric match. After geometric correction, cloud cover and cloud shadows were manually digitized and eliminated.

The database was processed by use of calibration and cross-calibration of the TM and ETM+ images (Vogelmann et al., 2001). Chander et al. (2004) and Teillet et al. (2004) identified an exponential decay of the solar reflective bands of Landsat 5-TM since 1984, with some differences between bands, so we applied equations proposed by Teillet et al. (2004) for correction. The coefficients of calibration for Landsat 7-ETM+ were obtained according to upper and lower at-satellite radiance levels indicated in the Landsat-7 Science Data Users Handbook (http://ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html). These values corresponded to date (before or after July 1, 2000) and type of gain (high or low, as embedded within the product format). Atmospheric correction was applied using the 6S radiative transfer model, which includes external atmospheric information (Vermote et al., 1997). In addition a non-Lambertian topographic correction was used to prevent errors caused by differences in illumination conditions (Teillet et al., 1982), and a relative normalization was employed for images of different dates (Du et al., 2002).

This procedure provided accurate measurements of physical surface reflectance units. The corrections applied to the images assured the temporal homogeneity of the dataset, absence of artificial noise due to sensor degradation and atmospheric conditions, and spatial comparability of different areas. Vicente-Serrano et al. (2008) provided details of the correction procedures.

3.2. Estimation of ice-covered area and snowline altitudes from remote sensing images

Snow and ice covered areas were discriminated from snow-free areas and cloudiness using the NDSI (Normalized Difference Snow Index), calculated from an equation that describes the relationship of the second band (TM2, visible) and fifth band (TM5, medium-infrared) of Landsat:

$$\text{NDSI} = (\text{TM2} - \text{TM5}) / (\text{TM2} + \text{TM5})$$

A pixel was mapped as snow or ice when the NDSI value was greater than 0.4 (Dozier, 1984). In order to validate the estimated ice covered area derived using the above mentioned methodology, we used an Ikonos image of September 2006 available from Google Earth, to be compared with the used Landsat image of August 2006. We selected one hundred of random points over the Huaytapallana sector, discriminating from the Ikonos image (with 82 cm of spatial resolution in the panchromatic) the ice covered and ice free areas. Selected points included areas very close to the edge of the glaciers, and surfaces covered by old ice with a high content of sediments. These points were tested with the discrimination done using the threshold of 0.4 of the NSDI derived from Landsat. All the points were properly classified, indicating the high accuracy achieved for estimating the area covered by ice in the region. The practically absence of debris covered glaciers in the region is an obvious advantage to ensure the accuracy of the ice covered surface estimation along the whole studied period.

Snowlines indicate the snow-ice boundaries and can be considered a proxy for the equilibrium-line altitude (Zemp et al., 2007). We used a supervised classification of each calibrated image to distinguish snow and ice within the glaciated surfaces (identified from calculation of the NDSI) and identified pure training areas representative of ice and snow based on visual inspection of each Landsat image. Discrimination was determined by use of the six reflective spectral bands of each image with a maximum likelihood Bayesian classifier, a method based on Bayes' theorem that incorporates prior knowledge. Maximum likelihood classification is based on the probability density function associated with a training site signature (Mather, 1985; Bolstad and Lillesand, 1991). A pixel is assigned to the most likely class based on comparison of the posterior probability that it belongs to each of the signatures being considered. After automatic classification of each image, we checked the validity of the final snow and ice classification by comparison of the type of surface visually identified at 75 random points in each image with the supervised classification. The accuracy of image classification was 83 to 96%.

We selected the years 1988, 1997, 2006, and 2010 to analyze the evolution of the mean elevation of the snowlines because these years had the least snow on top of the glaciers. In other words, during these years there was a lower probability of snow accumulation immediately prior to image acquisition. The elevation of the snowline varied significantly among different parts of the analyzed glaciers, so individual values were obtained for 20 glacier fronts of three areas of the Cordillera (Huaytapallana, Chapico, and Utcohuarco, Figure 6).

The 99th, 50th and 1st percentile of the frequency distributions of the elevation of the glaciated areas were used to estimate the upper, mean and lower elevations of the ice cover in each mountain area on different dates. Moreover, the frequency distribution of

elevation and potential incoming solar radiation was obtained for areas that were deglaciated during the study period. Mean annual potential incoming solar radiation under clear-sky conditions was calculated from the DEM model using the tool Solar Areal Radiation, implemented in ARC-GIS (Fu and Rich, 2002).

3.2 Climatic analysis

Climatic trends were analyzed from monthly series of precipitation and maximum and minimum temperatures from 11 observatories that were within 50 km of the Cordillera Huaytapallana. All selected time series had less than 10% missing data. Data was provided by the Peruvian Service of Meteorology and Hydrology (SENAMHI) and was subjected to a complete protocol of gap filling, quality control, and homogenization testing with an independent reference series (see González-Hidalgo et al., 2009). Monthly data for the period of 1965 to 2012 were aggregated for the wet season (October-April) and dry season (May-September). Series were standardized as anomalies of the long-term average in centigrade (°C) and percentage (%) for temperature and precipitation respectively. Then the eleven series were averaged to obtain a single regional series that described the main climate interannual signal of the focus (Borradile, 2003).

Moderate and strong El Niño and La Niña years during the study period were identified according to the Oceanic Niño Index (ONI), the standard used by NOAA to identify El Niño (warm) and La Niña (cool) events in the tropical Pacific (Smith et al., 2008). This is the running 3-month mean sea surface temperature (SST) anomaly for the Niño 3.4 region (*i.e.* 5°N-5°S, 120°-170°W). An event is defined as the presence of 5 consecutive months with an anomaly of at least +1°C for warm events (El Niño) or with an anomaly of at least -1°C for cold events (La Niña). The occurrence of El Niño and La Niña years are related to the interannual changes in the area covered by ice,

temperature, and precipitation. In the analysis of changes in glaciated surfaces, the lack of satellite images for several years prevented quantitative analysis, so only qualitative assessment was provided. Anomalies of temperature and precipitation observed during the different phases of the Southern Oscillation were compared by the Wilcoxon-Mann-Whitney test (Wilks, 2006), with a critical p -value less than 0.05, to identify significant differences in the monthly means of two subsets. Although parametric tests such as the t -test are more powerful for sample comparisons, the Wilcoxon-Mann-Whitney test is based on ranks and does not require normally distributed samples (Helsel and Hirsch, 1992).

3.4 Climate simulations of 2021 to 2050

Simulations of temperature and precipitation for the 20th and the 21st century developed by 20 modeling groups in the frame of the Coupled Modelling Integrated Project (CMIP 5, Taylor et al., 2012) were used to predict climate changes in this region from 2021 to 2050. We used the emission scenario defined by the Representative Concentration Pathways (RCPs) 2.6, which considers the lowest emission of greenhouse gases for the next few decades, based on an assumption of reduced emissions after the middle of the 21st century (Meinshausen et al., 2011). We selected this RCP to identify the minimum expected change in climate conditions in this region induced by anthropogenic causes. The average simulated precipitation and maximum and minimum temperatures for the period 2021-2050 was subtracted from the simulated values for the period 1980-2010 (control period) to calculate the magnitude of change.

4. Results

4.1 Changes in the ice-covered areas and snowline elevations

Table 1 shows the changes in the surface covered by ice, and the elevation of the upper, mean, and lower ice-covered areas in the six mountainous areas of the Cordillera Huaytapallana during the study period. The values for 1984 and 2011 were obtained from the ends of the linear trends of the temporal series of annual ice cover. In this way, these estimations of changes are more robust than a simple comparison of 1984 and 2011. The results indicate that ice cover decreased dramatically in all 6 areas. For the whole Cordillera Huaytapallana the 56% of the surface covered by ice has disappeared, decreasing from 50.2 km² in 1984 to 22.05 km² in 2011. For the 3 areas at the lowest elevations and with the least glaciated areas (Pitita, Marairazo and Azulcocha), glaciers disappeared completely or had less than 1 km² of ice cover area. In the Chapico and Utcohuarco areas, glaciers covered only 3.45 and 2.9 km² in 2011, about one-third of the areas that they covered in 1984 (9.8 and 8.2 km²). It is remarkable that the summit areas (above 5000 m a.s.l.) also lost ice cover, as indicated by the slight decrease in the upper elevations of the 6 glaciers (0-56 m), and that the lower elevations of the 6 glaciers were 115 to 366 m higher in 2011. Huaytapallana, the main glaciated area of the Cordillera, had 14.9 km² of glaciated cover in 2011, 42% of that in 1984 (26.5 km²). The lower elevation of this glacier increased by 115 m, but the upper elevation did not change, because the summit of the Huaytapallana (or Lazuntay) peak remained covered by ice.

Figure 3 shows the distribution of glaciers in the Huaytapallana area in 2011 and 1984. This figure shows that a significant amount of this surface (11.7 km²) was deglaciated. Analysis of the accumulated frequency distribution of the deglaciated surface during the study period indicated that 80% of the ice lost was in areas below 5100 m a.s.l., and that ice cover was mostly lost in slopes that received higher solar radiation (Figure 4). Figure 3 also shows that 11 new small and medium size lakes were

formed in the deglaciaded areas during the study period. Most of the new lakes are on the north side of the ridge, coinciding with the faster thawing of the ice in this region.

Figure 5 shows the annual changes of the ice-covered surface in whole Cordillera Huaytapallana (sum of all six areas). This data shows a decrease from 55.6 to 24.8 km² (44%). Most of the ice losses occurred from 1984 to 1997, when the ice-covered area was reduced by 31.6 km². This period coincided with a high frequency of El Niño events (1987, 1991, 1992, 1994 and 1997). The only La Niña event during this first part of the series was in 1988, and this was followed by a slight increase of the glacial surface in 1989. From 1997 to 2011, the ice cover continued to decrease, but at a slower rate. There were four La Niña events during this period (1998, 2000, 2008 and 2011) and most of them coincided with a slight increase of the area covered by ice. There were only two El Niño events during this period (2002 and 2009), and they seem unrelated to the largest ice losses during this period.

Figure 6 shows our analysis of the glacier fronts of the Huaytapallana, Chapico and Hutcohuarco areas (upper panels), and their changes in snowline elevation (lower panels). In these three areas, there was a notable increase in mean snowline elevation. In particular, the mean snowline elevation moved from 4983 m a.s.l. (1988) to 5075 m a.s.l. (2010) in Huaytapallana, from 4728 m a.s.l. (1988) to 4895 m a.s.l. (2010) in Chapico, and from 4797 m a.s.l. (1988) to 4890 m a.s.l. (2010) in Hutcohuarco. This figure also shows that there was significant variability in the temporal evolution and magnitude of change of the different glacier fronts.

4.2. Temperature and precipitation trends

Figure 7 shows the interannual evolution of maximum and minimum temperatures during the wet and dry seasons from 1965 to 2011. There was marked

interannual variability in all of these series, and there were also long-term general trends. The minimum temperature during the dry season had a statistically significant decrease of $-0.10^{\circ}\text{C decade}^{-1}$ ($\alpha < 0.05$); the minimum temperature during the wet season had an increase of $0.06^{\circ}\text{C decade}^{-1}$, but this was not significant ($\alpha > 0.05$). The evolution of minimum temperatures during the time period when glacier analysis was available (1984-2011) was very similar to that for the entire period ($-0.13^{\circ}\text{C decade}^{-1}$ vs. $-0.10^{\circ}\text{C decade}^{-1}$ and $0.04^{\circ}\text{C decade}^{-1}$ vs. $0.06^{\circ}\text{C decade}^{-1}$, respectively).

The maximum temperature had significant increases ($\alpha < 0.05$ for both) during the wet and dry seasons. For the full period (1965-2011), the wet and dry seasons each had a warming rate of $0.22^{\circ}\text{C decade}^{-1}$. During the period when glacier analysis was available (1984-2011), these trends were slightly lower, but still significant ($0.17^{\circ}\text{C decade}^{-1}$ for the wet season and $0.28^{\circ}\text{C decade}^{-1}$ for the dry season).

Figure 8 shows the interannual variability of precipitation during the wet and dry seasons. During the wet season, there was a significant long-term increase in precipitation from 1965 to 2011. Interestingly, the period of 1984 to 2011 is characterized by a dominance of negative anomalies until 1995, and a dominance of positive anomalies from 1995 to 2011. The dry season is characterized by significant alternations of short periods of positive and negative anomalies, with an overall long-term negative trend.

Figure 9 shows boxplots of the frequency distribution of maximum and minimum temperatures and precipitation for El Niño years, La Niña years, and other years (neither El Niño nor La Niña). During the dry season (3 plots on the right of Fig. 9), there were no remarkable differences in temperature or precipitation for these 3 phases. However, during the wet season (3 plots on the left of Fig. 9), an Wilcoxon-Mann-Whitney test indicated statistically significant differences ($\alpha < 0.05$) in minimum

and maximum temperatures during El Niño and La Niña years. In particular, 75% of the years classified as El Niño had positive anomalies in temperature, but all years classified as La Niña had negative anomalies. The other years were intermediate, and had means close to the long-term average, although there were some years with positive and negative anomalies. In other words, fewer temperature anomalies occurred during years not classified as El Niño or La Niña. Precipitation was not significantly different among the three groups during the wet season. However, La Niña years had the highest mean precipitation, and 75% of El Niño years had negative anomalies.

4.3 Projected temperature and precipitation change for the period 2021-2050

Finally, Figure 10 shows the mean and 75th and 25th percentiles of forecasted changes in precipitation and temperature from the General Circulation Models participating in the CMIP 5 project for the period of 2021 to 2050 relative to the 1981-2010 control period under the Representative Concentration Pathway (RCP) 2.6. This analysis forecasts that precipitation will remain very similar to that observed during the control period. Thus, 50% of the models forecast changes less than 5%. Temperature is forecasted to continue increasing for the next several decades during the wet and the dry seasons. Analyses of inter-model averages indicate an increase of maximum temperature of 1.3°C during the wet season and 1.2°C during the dry season.

5. Discussion and Conclusions

This paper analyzed changes in the surface area of glaciers, snowline elevation, temperature, and precipitation of the Cordillera Huaytapallana of Central Peru from 1984 to 2011. During this period, there was a 56% decrease in the area covered by

glaciers. Glaciers at the lowest elevations and those that received the most solar radiation underwent faster deglaciation, although summit areas also lost ice cover.

The rate of glacier retreat in Huaytapallana reported here is double than that reported for Cordillera Blanca (Bury et al., 2011; Fraser, 2012). This is probably because of the lower elevation of the Cordillera Huaytapallana. Tropical glaciers at elevations lower than 5400 m a.s.l. are very unstable, in contrast to high-elevation tropical glaciers, whose changes are more modest, and these high elevation glaciers may even undergo positive mass balances (Rabatel et al., 2013). Indeed, different areas of the Cordillera Huaytapallana have experienced very different rates of ice cover loss; in those at lower elevations the losses were greatest. Thus in the three areas whose summits were close to 5000 m a.s.l., some glaciers have completely melted or now have less than 1 km² area. The two areas with intermediate glaciated surface and whose summits are 5150 and 5300 m a.s.l. have lost two-thirds of their glaciated surface since 1984. However, the main area (Huaytapallana), which has significant surfaces above 5000 m a.s.l., lost only 42% of its ice cover. Zubieta and Lagos (2010) also analyzed this last area for the period of 1976-2006, and they reported an ice loss of 59%.

The snowline in Cordillera Huaytapallana has moved upward in elevation by 93 to 157 meters, depending of the mountain area. These values are in close agreement with those reported for Cordillera Raura (97 meters), and are significantly greater than those reported for Cordillera de Huayhuash (24 meters) for the period of 1986 to 2005 (Mc Fadden et al., 2011). These differences seem to be related to the initial snowline elevations of these different Cordilleras. Thus in 1984, snowlines in Cordillera Huaytapallana were between 4728 and 4890 m a.s.l. for the three analyzed areas, in 1986 the snowline in Cordillera Raura was at 4947 m a.s.l. and the snowline in Cordillera Huayhuash was at 5062 m a.s.l.. In other words, glaciers at lower elevations

appear more sensitive to climate change. The same effect seems to be operating at the low-elevation glaciers of the Cordillera Blanca, in which Yanamarey Glacier, which does not exceed 5200 m a.s.l., is retreating at a rate greater than 30 m year⁻¹ (Bury et al., 2011).

About 80% of the glacier retreat that we documented for the Cordillera Huaytapallana occurred from 1984 to 1997. The period from 1998 to 2011 was characterized by alternations of stability, slight increases, and slight decreases of glacier area. Studies of climate changes in the Tropical Andes have reported increases in air temperature (0.1°C decade⁻¹ between 1939 and 2006; Vuille et al., 2008). Recent studies estimated a warming rate of 0.39° C decade⁻¹ for the late 20th century in Cordillera Blanca (Mark and Seltzer, 2005), 0.2° C decade⁻¹ in Cordillera Huayhuash (Mac Fadden et al., 2011), and 0.2° C decade⁻¹ in Cordillera Vilcanota (Salzmann et al., 2013). In Cordillera Huaytapallana, minimum temperature increased slightly during the wet season and decreased slightly during the dry season. However, maximum temperature increased 0.22°C decade⁻¹ overall for the period of 1965 to 2011. Precipitation in this region also increased during the wet season from 1965 to 2011. Thus, glacier retreat in this region seems to be related to the increased temperature, because a temperature-induced change from snow to rain can increase glacier decline, and because glacial ablation is greater in a warmer climate (Francou et al., 2003). However, it is necessary to assess the effects of other components of the energy and mass balance of these glaciers on changes in ice cover. For example, an increase in the elevation of the snowlines documented here and changes in the phase of the precipitation (from snow to rain) might also affect the albedo of the glaciers (Favier et al., 2004). In addition, increased precipitation is probably associated with greater cloudiness and higher atmospheric humidity. Several authors have documented an increase in water vapor in

the Tropical Andes (Hense et al., 1988; Vuille et al., 2003), and this could lead to an increase in long-wavelength radiation (Ohmura, 2001) and attenuation of the turbulent flux that increases the availability of energy for the melting of ice (Sicart et al., 2005).

The results presented here indicate that ENSO appeared to affect temperature and precipitation in the Cordillera Huaytapallana. In other mountains of Peru and Bolivia, El Niño years are characterized by higher temperatures and less precipitation, with an opposite pattern for La Niña years (Garreaud and Aceituno, 2001; Vuille et al., 2008; Lagos et al., 2008). The same general pattern occurred in Cordillera Huaytapallana, but only temperature (not precipitation) was significantly different in El Niño and La Niña years. However, other studies reported significant negative correlations (Lagos et al., 2005), or less significant correlations (Silva et al. 2008), between the warm phase of ENSO and precipitation during the peak of the rainy season in the Mantaro basin of Peru. This resulted in a particularly strong Niño 4 SST index (averaged over 160°E–150°W, 5 °S–5 °N), which indicates an indirect effect of SST on the Mantaro basin, most likely through atmospheric teleconnections (e.g. Garreaud and Aceituno, 2001). In Cordillera Blanca, Kaser et al. (2003) and Vuille et al. (2008b) found that negative mass balance deviations usually occur during El Niño years and positive mass balance deviations usually occur during La Niña years. However, these authors also noted the presence of deviations from this pattern. Our results are in line with these findings. In general, El Niño years were associated with marked decreases in the ice cover in Huaytapallana, and La Niña years were associated with stability or slight increases in the ice cover. Thus, the observed acceleration of deglaciation in the Cordillera Huaytapallana from 1984 to 1997 can be attributed to the large number of El Niño events during that period; in contrast, La Niña events were more common from 1998 to 2011, and there was much less deglaciation during that period. In addition, there

were also deviations in this general pattern in Huaytapallana, which is not surprising given the large variations in temperature and precipitation in years not classified as El Niño or La Niña .

We ran climate models based on the most optimistic greenhouse gas emission scenario (RCP 2.6) to forecast changes in our study region from 2021 to 2050. The results indicated an increase in temperature by more than 1.2°C, but only minor changes in precipitation. Other more pessimistic scenarios for Peruvian mountain regions have forecasted increases in temperature of 2-3°C by the year 2050 (Bradley et al., 2004; Juen et al., 2007). Based on our observations of glaciers in Huaytapallana during the study period, an increase of 1.2°C (predicted by the “best case” scenario) would lead to the disappearance or near-disappearance of glaciers in all areas that we studied except in the Huaytapallana area, although glaciers in that region would also be severely affected. These changes could have great impact on the hydrology of the Mantaro basin, especially in the Sholcas sub-basin that drains the most important glaciated area. Moreover, the formation of new lakes in unstable high mountain environments is likely to continue, and this may lead to increased risk of flooding, especially because of the very steep and crevassed nature of these glaciers. The present study provides a foundation for a better understanding of the effect of climate change on glaciers and of the evolution of newly formed glacial lakes in this region. This information is required to provide better forecasts of future changes and to improve the responses to the forecasted changes in hydrology, ecology, and natural hazards.

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REFERENCES

- Agencia Nacional del Agua del Perú (ANA), 2010. *Evaluación de recursos hídricos superficiales en la cuenca del Río Mantaro*. Ed. Ministerio de Agricultura, Agencia nacional del Agua, Lima, 127p.
- Ames, A., 1998. A documentation of glacier tongue variations and lake development in the Cordillera Blanca, Peru. *Zeitschrift für Gletscherkunde und Glazialgeologie*, 34(1), 1–36.
- Arroyo, J., 2011. Tendencias y cambio del clima del valle del Mantaro mediante los análisis de índices de precipitación efectiva y temperatura eficiente. *Apuntes de Ciencias Sociales* (01), 45-54.
- Bradley, R. S., Keimig, F. T., Diaz, H. F., and Hardy, D. R., 2009. Recent changes in freezing level heights in the Tropics with implications for the deglaciation of high mountain regions, *Geophys. Res. Lett.*, 36, L17701, doi:10.1029/2009GL037712, 2
- Brecher, H. H., Thompson, L. G., 1993. Measurement of the retreat of Qori Kalis Glacier in the Tropical Andes of Peru by terrestrial photogrammetry, *Photogramm. Eng. Rem. S.*, 59, 1017–1022.
- Bolstad, P.V., Lillesand, T.M., 1991. Rapid maximum likelihood classification. *Photogrammetric Engineering & Remote Sensing* 57 (1), 67-74.
- Borradaile, G., 2003. *Statistics of Earth Science Data*. Ed. Springer-Verlag, Berlin: 248 p.
- Bury, J.T., B.G. Mark, J.M. McKenzie, A. French, M. Baraer, K. In Huh, M. A. Zapata Luyo, R. J. Gomez Lopez, 2011. Glacier Recession and Human Vulnerability in the Yanamarey watershed of the Cordillera Blanca, Peru. *Climatic Change* 105, 179–206.

Carey, M., 2005. Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru. *Global and Planetary Change* 47, 122–134.

Carey, M., Huggel, C., Bury, J., Portocarrero, C., Haeberli, W., 2012. An integrated socio-environmental framework for climate change adaptation and glacier hazard management: Lessons from Lake 513, Cordillera Blanca, Peru, *Climatic Change* 112, 733–767.

Chander, G., Helder, D. L., Markham, B. L., Dewald, J. D., Kaita, E., Thome, K. J., Micijevic, E., Ruggles, T. A., 2004. Landsat-5 TM reflective-band absolute radiometric calibration. *IEEE Transactions on Geoscience and Remote Sensing*, 42, 2746–2760.

Chavez P. S., 1996. Image-based atmospheric correction — Revisited and improved. *Photogrammetric Engineering and Remote Sensing* 62(9), 1025–1036.

Chevalier P, Pouyand B, Suarez W, Condom T., 2011. Climate change threats to environment in the Tropical Andes: glaciers and water resources. *Regional Environmental Change* 11 (1), 179-187.

Dorbath, L., Dorbath, C., Jimenez, E. and Rivera, L., 1991. Seismicity and tectonics deformation in the Eastern cordillera and the sub-andean zone of central Peru. *Journal of South American Earth Sciences* 4, 13-24.

Dozier J., 1989. Spectral signature of alpine snow cover from the Landsat Thematic Mapper. *Remote Sensing Environment* 28, 9-22.

Du, Y., Teillet, P., Cihlar, J., 2002. Radiometric normalization of multitemporal high resolution satellite images with quality control and land cover change detection. *Remote Sensing of Environment* 82, 123–134.

534 Favier, V., Wagnon, P., Chazarin, J.-P., Maisincho, L., Coudrain, A., 2004. One-year
535 measurements of surface heat budget on the ablation zone of Antizana glacier 15,
536 Ecuadorian Andes. *J. Geophys. Res.* 109, D18105.

537 Francou, B., Vuille, M., Wagnon, P., Mendoza, J., Sicart, J.E., 2003. Tropical
538 climate change recorded by a glacier in the central Andes during the last decades of the
539 20th century: Chacaltaya, Bolivia, 16S. *J. Geophys. Res.* 108, D5, 4154.

540 Francou, B., Vincent, C. 2007, *Les glaciers à l'épreuve du climat*, IRD Editions,
541 274p.

542 Fraser B., 2012. Melting in the Andes: Goodbye glaciers. *Nature* 491, 180-182.

543 Fu, P., and P. M. Rich. 2002. "A Geometric Solar Radiation Model with Applications
544 in Agriculture and Forestry." *Computers and Electronics in Agriculture* 37, 25–35.

545 Helsel, D.R., Hirsch, R.M., 1992, *Statistical Methods in Water Resources*, Elsevier,
546 522 p.

547 Juen I, Kaser G., Georges C., 2007. Modeling observed and future runoff from a
548 glacierized tropical catchment (Cordillera Blanca, Perú). *Global and Planetary Change*
549 59 (1–4), 37–48.

550 Garreaud, R. D., Aceituno, P., 2001. Interannual rainfall variability over the South
551 American Altiplano. *Journal of Climate* 14, 2779-2789.

552 Hense, A., Krahe, P., Fehner, H., 1988. Recent fluctuations of tropospheric
553 temperature and water vapour content in the tropics. *Meteorol. Atmos. Phys.* 38, 215-
554 227.

555 Kaser, G., Osmaston, H. A., 2002. *Tropical Glaciers*, Cambridge University Press,
556 New York, 209 pp.

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

560 Lagos, P., Silva, Y., Nickl, E., 2005. El Niño y la precipitación en los Andes del
561 Perú. *Boletín de la Sociedad Geológica de Lima Vol. especial 6* Alberto Giesecke
562 Matto, p. 7-23.

563 Mather, P.M., 1985. A computationally-efficient maximum-likelihood classifier
564 employing prior probabilities for remotely-sensed data. *International Journal of Remote*
565 *Sensing* 6 (2), 369-376

566 McFadden, E. M., Ramage, J., Rodbell D.T., 2011. Landsat TM and ETM+ derived
567 snowline altitudes in the Cordillera Huayhuash and Cordillera Raura, Peru, 1986-2005.
568 *The Cryosphere*, 5, 419-430

569 Instituto Geofísico del Perú (IGP), 2010. Cambio climático en la cuenca del Río
570 Mantaró. Ed. Instituto Geofísico del Perú, Lima, 260p.

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

574 Meinshausen, M., S. J. Smith, K. V. Calvin, J. S. Daniel, M. L. T. Kainuma, J.-F.
575 Lamarque, K. Matsumoto, S. A. Montzka, S. C. B. Raper, K. Riahi, A. M. Thomson,
576 G., Velders, J.M., van Vuuren, D., 2011. The RCP Greenhouse Gas Concentrations and
577 their Extension from 1765 to 2300. *Climatic Change* 109 (1-2): 213-241.

578 Messerli, B., 2001. The international year of the mountains, the Mountain Research
579 Initiative, and PAGES editorial. *Past Global Changes News* 9 (3), 2.

580 Peduzzi, P., Herold, C., Silverio, W., 2010. Assessing high altitude thickness,
581 volume and changes using field, GIS and remote sensing techniques: the case of Nevado
582 Coropuna (Peru). *The Cryosphere* 4, 313–323.

583 Portocarrero, C. 1995 Retroceso de glaciares en el Perú: Consecuencias sobre los
584 recursos hídricos y los riesgos geodinámicos. *Bulletin de L’Institut Francais d’Études*
585 *Andines* 24(3):697–706.

586 Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J. L.,
587 Basantes, R., Vuille, M., Sicart, J.-E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y.,
588 Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galarraga, R., Ginot, P.,
589 Maisincho, L., Mendoza, J., Ménégos, M., Ramirez, E., Ribstein, P., Suarez, W.,
590 Villacis, M., Wagnon, P., 2013. Current state of glaciers in the tropical Andes: a multi-
591 century perspective on glacier evolution and climate change, *The Cryosphere* 7, 81-102.

592 Raup, B., Racoviteanu, A., Khalsa, S.J.S., Helm, C., Armstrong, R., Arnaud, Y.,
593 2007. The GLIMS geospatial glacier database: a new tool for studying glacier change.
594 *Global Planet. Change* 56 (1–2), 101–110.

595 Reynolds, J. M.. 1992. The identification and mitigation of glacier-related hazards:
596 Examples from the Cordillera Blanca, Peru. In: McCall, G. J. H., Laming, D. C. J. and
597 Scott, S. (eds), *Geohazards*, London, Chapman & Hall, 143–157.

598 Salzmann, N., Huggel, C., Rohrer, M., Silverio, W., Mark, B. G., Burns, P., and
599 Portocarrero, C. 2013. Glacier changes and climate trends derived from multiple sources
600 in the data scarce Cordillera Vilcanota region, southern Peruvian Andes, *The*
601 *Cryosphere* 7, 103-118.

602 Silva, Y., Takahashi, K., Chávez, R., 2008: Dry and wet rainy seasons in the
603 Mantaro river basin (Central Peruvian Andes). *Advances in Geosciences* 14, 261-264.

Racoviteanu, A.E., Manley, W., Arnaud, Y., Williams, M.W., 2007. Evaluating digital elevation models for glaciologic applications: an example from Nevado Coropuna, Peruvian Andes. *Global and Planetary Change* 59 (1–4), 110–125.

Seimon, T.A., Seimon, A., Daszak, P., Halloy, S.R.P., Schloegel, L.M., Aguiar, C.A., Sowell, P., Hyatt, A.D., Konecky, B., Simmons, J.E., 2007. Upward range extension of Andean anurans and chytridiomycosis to extreme elevations in response to tropical deglaciation. *Global Change Biology* 13, 288–299.

Sicart, J.-E., Wagnon, P., Ribstein, P., 2005. Atmospheric controls of heat balance of Zongo Glacier (16° S, Bolivia), *J. Geophys. Res.* 110, D12106

Smith, T. M., Reynolds, R.W., Peterson, T.C., Lawrimore, J., 2008. Improvements to NOAA’s Historical Merged Land–Ocean Surface Temperature Analysis (1880–2006). *J. Climate* 21, 2283–2296.

Taylor, K. E., Stouffer, R. J., Meehl, G. A., 2012. An overview of CMIP5 and the experimental design, *Bull. Am. Meteorol. Soc.* 93, 485–49.

Teillet, P. M., Guindon, B., & Goodeonugh, D. G. (1982). On the slope-aspect correction of multispectral scanner data. *Canadian Journal of Remote Sensing*, 8, 84–106.

Teillet, P. M., Barker, J. L., Markham, B. L., Irish, R. R., Fedosejevs, G., & Storey, J. C., 2001. Radiometric cross-calibration of the Landsat-7 ETM+ and Landsat-5 TM sensors based on tandem data sets. *Remote Sensing of Environment* 78, 39–54.

Teillet, P. M., Helder, D. L., Ruggles, T. A., Landry, R., Ahern, F. J., Higgs, N. J., Barsi, J., Chander, G., Markham, B. L., Barker, J. L., Thome, K. J., Schott, J. R., Palluconi, F. D., 2004. A definitive calibration record for the Landsat-5 Thematic Mapper anchored to the Landsat-7 radiometric scale. *Canadian Journal of Remote Sensing* 30, 631–643.

Leon, B. Les, D., Lin, P. N., Mashiotta, T., Mountain, K. 2006. Abrupt tropical climate change: Past and present. *Proceedings National Academy of Sciences (PNAS)* 103, 10536–10543.

Vermote, E. F., Tanré, D., Deuzé, J. L., Herman, M., Morcrette, J. J., 1997. Second simulation of the satellite signal in the solar spectrum, 6S: an overview. *IEEE Transactions on Geoscience and Remote Sensing* 35, 675–686.

Vicente-Serrano, S.M., Pérez-Cabello, F., Lasanta, T., 2008. Assessment of radiometric correction techniques in analyzing vegetation variability and change using time series of Landsat images. *Remote Sensing of Environment* 112: 3916-3934.

Vogelmann, J. E., Helder, D., Morfitt, R., Choate, M. J., Merchant, J.W., Bulley, H., 2001. Effects of Landsat 5 Thematic Mapper and Landsat 7 enhanced Thematic Mapper Plus radiometric and geometric calibrations and corrections on landscape characterization. *Remote Sensing of Environment* 78, 55–70.

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. *Climatic Change* 59 (1–2), 75–99.

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B. G., Bradley, R. S., 2008a. Climate change and tropical Andean glaciers: Past, present and future, *Earth-Sci. Rev.* 89, 79–96.

Vuille, M., Kaser, G., Juen, I. 2008b Glacier mass balance variability in the Cordillera Blanca, Peru and its relationship with climate and the large-scale circulation, *Glob. Planet. Change* 62, 14–28.

653 Wagnon, P., Ribstein, P., Francou, B., and Pouyaud, B., 1999. Annual cycle of
 654 energy balance of Zongo Glacier, Cordillera Real, Bolivia, J. Geophys. Res. 104, 3907–
 655 3923.

656 Wilks, D. S., 2006. Statistical Methods in the Atmospheric Sciences, second ed.
 657 Academic Press. 618pp.

658 Zemp, M., Hoelzle, M. and Haeberli, W. (2007): Distributed modelling of the regional
 659 climatic equilibrium line altitude of glaciers in the European Alps. Global and Planetary
 660 Change 56, 83–100.

661 Zubieta, R., Lagos P., 2010. Cambios de la superficie glaciar en la cordillera
 662 Huaytapallana: Periodo 1976– 2006, in: Cambio climático en la cuenca del río Mantaro:
 663 Balance de 7 años de estudio en la cuenca del Mantaro. Instituto Geofísico del Perú.
 664 Lima, 260pp.

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Figure captions

Figure 1. Map of the study region with the location of the 6 studied areas in the Cordillera Huaytapallana and the meteorological stations (blue dots). The numbers indicate the stations shown in Figure 2 (1: Tunelcero, 2: Jauja).

Figure 2. Long-term average monthly precipitation (vertical bars), maximum temperature (red solid line), and minimum temperature (blue dashed line) at two meteorological stations in the study region.

Figure 3. Coverage of glaciers (yellow: 1984, green: 2011) and lakes (blue: existing in 1984, red: formed since 1984) in the Huaytapallana area from 1984 to 2011.

Figure 4. Accumulated frequency distribution of elevation (A) and potential incoming radiation (B) of deglaciaded surfaces (%) in the Cordillera Huaytapallana from 1984 to 2011.

Figure 5. Annual changes in the ice-covered area in the Cordillera Huaytapallana during the study period. El Niño events (O) and la Niña events (A) are indicated.

Figure 6. Upper panels: Changes in the elevation of the snowlines of 3 areas (red: 1988, yellow: 1997, blue: 2006, green: 2010). Lower panels: Quantitation of data in the upper panels, showing the elevation of snowline in each glacier front (grey dots) and the average of each area (black dots) for the years 1988, 1997, 2006 and 2010.

Figure 7. Changes of minimum temperature (upper panel) and maximum temperature (lower panel) during the wet season (October-April; black line) and the dry season (May-August; grey dashed line) from 1965 to 2011. The vertical dashed line indicates the time when glacier analysis began. The trends for maximum temperature were $0.22^{\circ}\text{C decade}^{-1}$ for the wet and dry seasons for 1965-2011, $0.17^{\circ}\text{C decade}^{-1}$ for the wet season for 1984 to 2011, and $0.28^{\circ}\text{C decade}^{-1}$ for the dry season for 1984-2011.

Figure 8. Changes in precipitation during the wet season (October-April; upper panel) and the dry season (May-August; lower panel) from 1965 to 2011. The vertical dashed line indicates the time when glacier analysis began. Precipitation anomalies (%) are shown as blue bars (positive) or red bars (negative) relative to the 1965-2011 mean.

Figure 9. Boxplots of the frequency distribution of maximum and minimum temperature and precipitation during El Niño years, La Niña years, and other years. The black central line indicates the mean, the upper and lower lines of the boxes indicate the 75th and 25th percentiles, the upper and lower bars indicate the 90th and 10th percentiles, and the black dots indicate 95th and 5th percentiles. Temperature and precipitation anomalies are shown as deviations from the 1965-2011 mean.

Figure 10. Mean (dots) and 75th and 25th percentiles (bars) of the change in precipitation and temperature projected by the General Circulation Models in the CMIP 5 project for the 2021-2050 period relative to the 1981-2010 control period under the Representative Concentration Pathway (RCP) 2.6.

Table 1. Change in glacier extent, upper (99th percentil), mean (50th percentil) and lower (1st percentil) elevation of glaciers in the Cordillera Huaytapallana during the period 1984-2011.

	Area (Km ²)			Upper elevation (m a.s.l.)			Mean elevation (m a.s.l.)			Lower elevation (m a.s.l.)		
	1984	2011	Dif.	1984	2011	Dif.	1984	2011	Dif.	1984	2011	Dif.
Huaytapallana	26.5	14.9	-11.6	5555	5555	0	5059	5130	-71	4600	4715	-115
Chapico	9.8	3.45	-6.35	5309	5288	-21	4849	4925	-76	4439	4686	-247
Utcohuarco	8.2	2.9	-5.6	5145	5133	-12	4796	4875	-79	4394	4760	-366
Pitita	3.8	0.7	-3.1	5078	5075	-3	4748	4818	-70	3835	4061	-226
Marairazo	1.6	0.1	-1.5	5056	5000	-56	4813	4931	-118	4540	4715	-175
Azulcocha	0.3	ND	ND	4900	ND	ND	4684	ND	ND	4494	ND	ND
Total	50.2	22,05	28.1									

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726 **Figure 1.** Map of the study area showing location of the 6 glaciers of interest in the
727 Cordillera Huaytapallana and the meteorological stations used here (in blue dots). The
728 numbers indicate the stations analyzed in Figure 2, i.. 1:Tunelcero; 2:Jauja.

Figure 2. Long-term average monthly precipitation (vertical bars), maximum (red solid line) and minimum (blue dashed line) temperature in two selected meteorological stations.

Figure 3. Glacier extent in the Huaytapallana sector in 1984 and 2011. Lakes existing in 1984 are coloured in blue. Lakes formed during the studied period are coloured in red.

Figure 4. Accumulated frequency distribution of elevation (A) and potential incoming radiation (B) of deglaciaded areas (in %) during the period 1984-2011.

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749 **Figure 5.** Interannual evolution of ice covered area. El Niño and la Niña events are
750 indicated with “O” and “A”, respectively.

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Figure 6. Upper panels: Glacier fronts where the evolution of elevation of the snowlines have been studied. Lower panels: Elevation of snowline in each glacier front (grey dots) and the average of each sector (black dots) for the years 1988, 1997, 2006 and 2010.

Figure 7. Temporal evolution of minimum (upper panel) and maximum (lower panel) temperatures during the wet (October-April; black line) and the dry (May-August; grey dashed line) 1965-2011 seasons. Vertical dashed lines indicates the start of the analysed 1984-2011 period. Reported temperature trend (in °C per decade-1) is shown for both 1965-2011 and 1984-2011 (in brackets) periods.

Figure 8. Temporal evolution of precipitation during the wet (October-April; upper panel) and the dry (May-August; lower panel) 1965-2011 seasons. Vertical dashed lines indicates the start of the analysed 1984-2011 period. Precipitation anomaly (in %) is shown as deviation from the 1965-2011 mean.

Figure 9. Boxplots representing the frequency distribution of maximum and minimum temperature and precipitation of the years classified as El Niño, La Niña and the others. Black line indicates the mean, upper and lower part of the boxes indicate the percentiles 75th and 25th, respectively, upper and lower part of the bar indicate the 90th and 10th percentile, respectively. Temperature (in °C) and precipitation (in %) anomalies are shown as deviations from the 1965-2011 mean.

Figure 10. Mean (dots), 75th and 25th percentiles (bars) of the change in precipitation and temperature projected by the General Circulation Models participating in the CMIP 5 project for the 2021-2050 period, compared to the 1981-2010 control period under the Representative Concentration Pathway (RCP) 2.6.