Geocarto International

ISSN: 1010-6049 (Print) 1752-0762 (Online) Journal homepage: http://www.tandfonline.com/loi/tgei20

Variations in annual snowline and area of an ice-covered stratovolcano in the Cordillera Ampato, Peru, using remote sensing data (1986–2014)

Bijeesh Kozhikkodan Veettil, Ulisses Franz Bremer, Sergio Florêncio de Souza, Éder Leandro Bayer Maier & Jefferson Cardia Simões

To cite this article: Bijeesh Kozhikkodan Veettil, Ulisses Franz Bremer, Sergio Florêncio de Souza, Éder Leandro Bayer Maier & Jefferson Cardia Simões (2015): Variations in annual snowline and area of an ice-covered stratovolcano in the Cordillera Ampato, Peru, using remote sensing data (1986–2014), Geocarto International, DOI: 10.1080/10106049.2015.1059902

To link to this article: http://dx.doi.org/10.1080/10106049.2015.1059902

Geocarto International, 2015
http://dx.doi.org/10.1080/10106049.2015.1059902

Taylor & Francis
Taylor & Francis Group

Variations in annual snowline and area of an ice-covered stratovolcano in the Cordillera Ampato, Peru, using remote sensing data (1986–2014)

Bijeesh Kozhikkodan Veettil[a,b]*, Ulisses Franz Bremer[a,b], Sergio Florêncio de Souza[a], Éder Leandro Bayer Maier[c] and Jefferson Cardia Simões[b]

[a]*Centro Estadual de Pesquisas em Sensoriamento Remoto e Meteorologia (CEPSRM), Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, Brazil;* [b]*Centro Polar e Climático (CPC), Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, Brazil;* [c]*Institute of Social and Information Science, Federal University of Rio Grande (FURG), Rio Grande, Brazil*

(*Received 18 April 2015; accepted 26 May 2015*)

This research focuses on the recent variations in the annual snowline and the total glaciated area of the Nevado Coropuna in the Cordillera Ampato, Peru. Maximum snowline altitude towards the end of dry season is taken as a representative of the equilibrium line altitude of the year, which is an indirect measurement of the annual mass balance. We used Landsat and IRS LISS3 images during the last 30 years due to its better temporal coverage of the study site. It is found that there was a decrease of 26.92% of the glaciated area during 1986–2014. We calculated the anomalies in precipitation and temperature in this region and also tried to correlate the changes in glacier parameters with the combined influence of El Niño – Southern Oscillation (ENSO) and pacific decadal oscillation (PDO). It is concluded that the snowline of Nevado Coropuna has been fluctuated during ENSO, and maximum fluctuations were observed when ENSO and PDO were in phase.

Keywords: snowline; outer tropics; equilibrium line altitude; Nevado Coropuna; Cordillera Ampato

1. Introduction

Tropical glaciers in South America are observed to be shrinking since the Little Ice Age. A significant change in the tropical Andean climate is observed during the past few decades (Vuille et al. 2008). It is predicted that all tropical Andean glaciers at lower latitudes will disappear soon (Veettil et al. 2014), and this glacier recession is dependent on the climate variations. Changes in climate induces changes in atmospheric humidity, precipitation and cloudiness towards which the glaciers are sensitive (Vuille et al. 2008). The Andes is considered as the most important mountain range in the southern hemisphere like the Alps or the Himalayas in the northern hemisphere. It is observed that the percentage of warmer nights have been increased since the second half of twentieth century in South America, and this warming trend is not homogeneous in the eastern and western slopes of the Andean chain (Salzmann et al. 2009). Many people in the hyper-arid coastal lowlands and Altiplano in Bolivia and Peru rely on glacier meltwater for their freshwater needs during the dry season and

---

*Corresponding author. Email: bijeesh.veettil@ufrgs.br hence mountain glaciers can be considered as freshwater buffers in this region. Tropical mountain glaciers are considered as indicators of climate change as they grow or shrink with climate imbalances (Vuille et al. 2008). Tropical Andes (between 10°N and 16°S) is one of the suitable locations to study the climate change influence on tropical glaciers because these glaciers are subjected to higher daily temperature variations than annual temperature variation. Vuille et al. (2000) proposed that the rainfall variability towards the east of the equatorial Andes related more to the tropical Atlantic circulation anomalies than those in the Pacific. Another point on precipitation variability in the Andes is that the precipitation rate increases with altitude and observed particularly in the high altitude Ecuadorian Andes (Garreaud 2009). Precipitation is one of the variables that determine the growth/mass loss of glaciers in the tropical region and it is worthwhile to understand how the precipitation varies in this region of the Andes. It is also noted that the precipitation near the glaciers within the Amazon basin is higher compared to those near the Pacific (Veettil et al. 2014). The anomalies in temperature and precipitation associated with El Niño – Southern Oscillation (ENSO) were found to be weakening towards the Altiplano (Garreaud 2009).

The Peruvian Andes accommodates about 70% of the tropical glaciers (Vuille et al. 2008) and is the most extensive ice-covered tropical mountain range. An increase of about 0.1 °C per decade in the air temperature is reported in the central Andes (Vuille et al. 2008). The land cover in Peru can be divided into three geographical regions: Pacific coast, Cordillera of the Andes and the Amazonian forest (Chevallier et al. 2011). The Peruvian climate is highly influenced by the Andean mountain chain. Changes in the equilibrium line altitude (ELA) denote an immediate change in the mass balance of the glacier and a continuous change in ELA can be used to estimate the climate trend in that region on an interannual scale. It is identified that the ENSO and other global scale phenomena such as the pacific decadal oscillation (PDO) influence the Andean climate differently along its length (Garreaud 2009; Veettil et al. 2014). ENSO dominates in the Tropical Pacific in the southern hemisphere whereas PDO dominates in the North Pacific. It is known for ages that El Niño years were followed by decreased precipitation over northern South America. This is due to the inhibition of moisture transport from the Amazon basin due to strong westerly wind during El Niño (Vuille 2013). It is also noted that the river discharge during strong El Niño periods were higher towards northern Peru compared to those in the south (Lavado-Casimiro et al. 2013). Unfortunately, many of the hydrometeorological stations in Peru are discontinuous or not existing at present. Ice core records from Peru show a direct correlation between ENSO and glacier mass balance in the Peruvian Andes (Henderson et al. 1999; Thompson 2000; Herreros et al. 2009). Many papers are available on the fact that smaller glaciers in the Cordillera Blanca in Peru are disappearing recently (Racoviteanu et al. 2008; Salzmann et al. 2009; Rabatel et al. 2013). The Quelccaya ice cap in Peru is having one of the well-documented ice core records in the world (Thompson 2000).

Due to the availability of SPOT and Landsat series of images, it is possible to understand the overall decline in the glaciarized area in the Cordillera Blanca since the early 1970s (Vuille et al. 2008). Studies based on remote sensing have predicted that many glaciers in Peru, such as Yanamarey Glacier, would disappear within a decade (Huh et al. 2012). In this study, we calculated the annual changes in the area and annual snowline of a glaciated stratovolcano – Nevado Coropuna – in the Cordillera Ampato of Peru and tried to understand how these two glacier parameters changed with the phase changes of ENSO and PDO.

2. Study site and climate conditions

The Nevado Coropuna (Lat: 15°24′-15°51′ S; Long: 71°51′-73°00′ W) in the central volcanic zone (CVZ) in the Cordillera Ampato, southern Peru, is considered in this research (Figure 1). Cordillera Ampato is consisted of 93 glaciers with an average thickness of about 35 m and a total surface area of 146.73 km^2 based on aerial photography in 1962. The Nevado Coropuna is the highest peak (6426 m asl) in the Cordillera Ampato and the highest stratovolcano in Peru (Racoviteanu et al. 2007). Many people in the northern–western part of Arequipa city depend on the glacier melt water supply from Nevado Coropuna. Recent glacier shrinkage in the Cordilleras of Peruvian Andes is reported to be started in the second half of 1980s (Salzmann et al. 2012). Racoviteanu et al. (2007) found that the size of the Coropuna was decreasing from 82.6 km^2 in 1962 to 60.8 km^2 in 2000. Mass balance of glaciers in this region depends highly on the variations in precipitation (Wagnon et al. 1999).

Precipitation in the Coropuna region depends mainly on the easterly circulation of air masses from the tropical Atlantic Ocean (Herreros et al. 2009). However, the Pacific atmospheric circulation patterns are also having a significant role in determining the climate in this region. Like other glaciers in the subtropics and outer tropics, Nevado Coropuna is also having an ELA above the 0 °C isotherm, whereas those in the inner tropics are close to the 0 °C isotherm. Glaciers situated in the outer tropics and the subtropics are thus considered as temperature-insensitive (Kaser 1999). The east of the Atlantic Ocean and the Amazon basin control the precipitation in the tropical Andes, mainly by the seasonal easterly winds (Vuille & Keimig 2004). There are 15 meteorological stations operated by the Peruvian national meteorological and hydrological service within 60 km of the study site. Seasonal variation in temperature is small whereas that in precipitation is higher and about 70–90% of the precipitation occurs during the austral summer (December–March). Dry season in the tropical Andes of Peru is during the austral winter. Higher precipitation rates were observed on the east-facing slopes than the west-oriented ones, probably due to higher moisture transport from the Amazon basin. Decreased precipitation rates were observed during strong El Niño events during 1982–1983 and 1992 whereas a strong El Niño in 1997 was found to be not interfered with the observed precipitation rates (Herreros et al. 2009). Unfortunately, many of the meteorological and hydrological stations in this region stopped functioning or having incomplete data-sets. Figure 2 shows the monthly mean precipitation (MMP) at the Coropuna region derived from various meteorological stations near the Nevado Coropuna.

Various studies focused on monitoring the changes in glaciated area, ice volume or ice thickness of the Nevado Coropuna using remote sensing and GIS techniques (Racoviteanu et al. 2007; Peduzzi et al. 2010; Ubeda 2011). There are previous studies on the snowline variations of the Nevado Coropuna and other glaciers in the central Andes during the late Pleistocene (Bromley et al. 2009, 2011). The effects of recent warming in the tropics on the Nevado Coropuna using ice core records was published recently by Herreros et al. (2009). In this study, we used remotely sensed satellite images and digital elevation models (DEM) for monitoring the changes in the snowline altitude (SLA) of the Nevado Coropuna and also to calculate the annual changes in the area towards the end of the dry season (May–September). We also used precipitation and air temperature data from the University of Delaware.

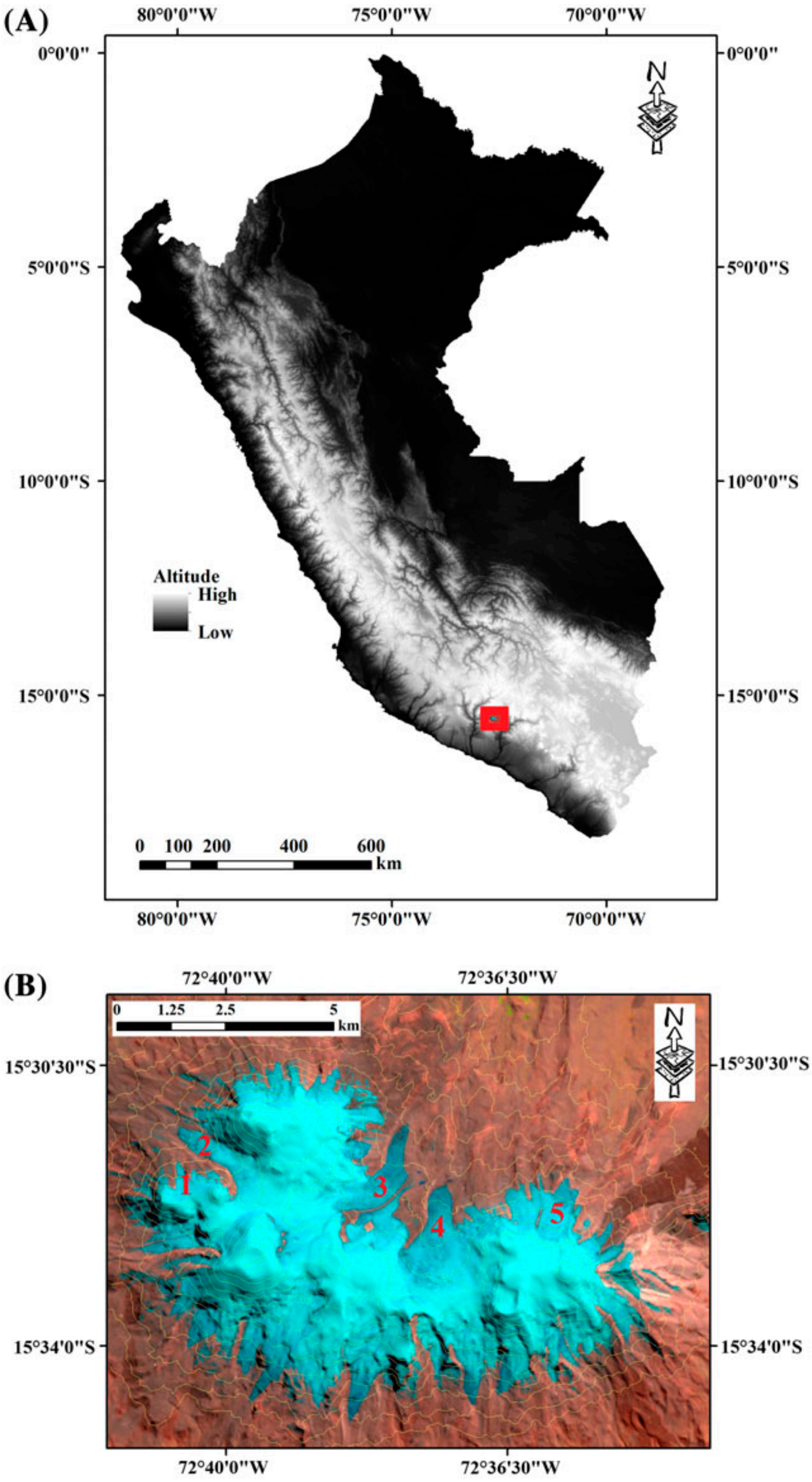

Figure 1. (A) Altitude distribution in Peru and the location of the Nevado Coropuna. (B) Selected glaciers for calculating the highest annual snowline.

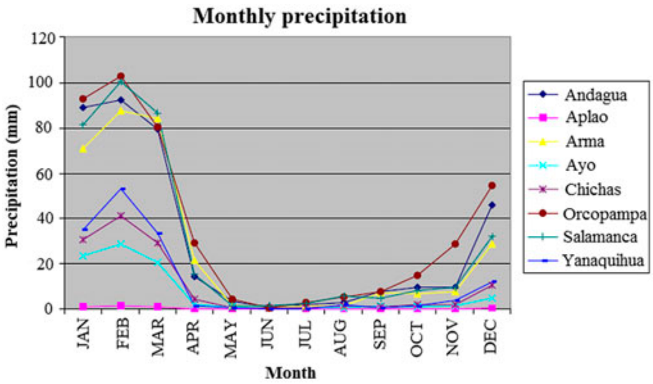

Figure 2. MMP measured by the meteorological stations near the Nevado Coropuna.
Source: Silverio 2005.

3. Data-sets

Landsat series of data are proved to be excellent in monitoring glacier surfaces, and many studies exist on the application of Landsat data in glaciology (Aniya et al. 2000; Albert 2002; Bamber & Rivera 2007; Racoviteanu et al. 2008) . Landsat bands in the VNIR contain the most valuable information to distinguish glacier surface characteristics (Pope & Rees 2014). Landsat series images (except Landsat 1–4) are having a spatial resolution of 30 m in the multispectral channels and only these wavelengths are used in this research. We also used an LISS3 image (spatial resolution: 23.5 m) from IRS-P6 in 2012 due to the discontinuity of the Landsat data in the same year. Other than multispectral images, we used DEM from ASTER GDEM V2 for calculating the surface properties of the study site. The DEM used here is having a vertical accuracy of approximately 20 m, which is having the same order of magnitude as the surface lowering and hence an altitudinal correction was not necessary (Rabatel et al. 2012). Moreover, the artefacts in SRTM caused by the penetration of C band in to the snow is absent in the ASTER GDEM.

In order to understand the influence of variabilities in the precipitation and temperature on the glacier mass loss in the study site, we used precipitation and temperature data from multiple sources for comparison. We used meteorological data from the University of Delaware in the form of gridded data-sets as well as from Servicio Nacional de Meteorología y Hydrología del Perú (SENAMHI). The gridded data-sets from Delaware are having a lat-long resolution of 0.5° × 0.5°. Ocean Niño Indices and PDO indices were downloaded from NOAA (http://www.cpc.ncep.noaa.gov).

4. Methodology and results

Identification of snow and ice using remote sensing is easy in theory, but in practice, it is not so straightforward (Albert 2002). This is because the spectral response of snow and ice varies with the quantity of impurities and meltwater above the ice and albedo changes with the ageing. Two satellite systems used for the last few decades, Landsat and SPOT, suffered from spatial and spectral resolution constraints, respectively. One of the drawbacks of using satellite images is that specific algorithms may be needed for images from place to place or season to season. Methods using Landsat series of images vary from simple false-colour composite and band ratios to principal component analysis, indices and object-oriented image analysis. In order to assure the accuracy and reduce the error, atmospherically corrected images were co-registered before further processing. One of the most efficient methods to map glaciers is the manual delineation. However, manual delineation is not applied here because a large number of images were used. We calculated the annual changes in the minimum area during the dry season and the maximum snowline from 1986 to 2014 to understand the influence of climatic perturbations on the Nevado Coropuna. In order to understand the glacier recession due to climate forcing, some of the variables such as atmospheric circulation and anomalies in temperature and precipitation are relevant. We calculated the anomalies in temperature and precipitation at the study site during the last 50 years and also considered two ocean-atmospheric phenomena in the Pacific – ENSO and PDO.

4.1. Variations in the annual minimum area of the Nevado Coropuna

The area of the glaciated surface and SLA can be used to understand the influence of climate change on glaciers in the outer tropics and subtropics. We tried to make sure that the images used were acquired towards the end of dry season (May–September) and images are cloud-free. In order to discriminate ice and other objects, we calculated normalized difference snow indices (NDSI) from Landsat and LISS3 images (Equations 1 and 2, respectively). NDSI images were calculated from the green (TM2: 0.52– 0.60 μm) and mid-infrared (TM5: 1.55 – 1.75 μm) channels.

$$\mathrm{NDSI} = [(\mathrm{TM2} - \mathrm{TM5})/(\mathrm{TM2} + (\mathrm{TM5})] \tag{1}$$

$$\mathrm{NDSI} = [(\mathrm{Band1} - \mathrm{Band4})/(\mathrm{Band1} + \mathrm{Band4})] \tag{2}$$

Glacier area can be calculated by applying a suitable threshold to the NDSI images. The threshold value to be applied to delineate glacier margin may vary from place to place and even from image to image (Wang & Li 2003). In this research, we used a threshold between 0.45 and 0.55 for Landsat images and 0.75 to 0.85 for the LISS3 images. By applying a suitable threshold, NDSI images can be used even when thin clouds are present in the image (Sidjak & Wheate 1999). Due to its robustness and easiness to apply, particularly when a large number of images are to be processed, Racoviteanu et al. (2008) used the NDSI method in the Cordillera Blanca. The observed changes in the annual minimum area of Nevado Coropuna during 1986–2014 are graphically represented in Figure 3.

It is seen from the Figure 3 that there was a decrease of 26.92% of the total glaciated area of the Nevado Coropuna from 1986 to 2014. There was a rapid decrease in the area during the El Niño episodes during 1997–1998, 2004–2005 and 2009–2010. It is also noticed that there was an increase in the area during the La Niña episodes in 1998–1999, 2001–2002 and 2010–2011. This indicates that the response of mountain glaciers to the ENSO in the Cordillera Ampato is rapid (whereas glaciers in Bolivia or Ecuador were found to show a delayed response towards ENSO). However, length (horizontal) changes in the terminus may or may not represent a change in the mass balance when the ice thickness is unknown (Bamber & Rivera 2007) or the case of surging glaciers (Aniya et al. 2000) and hence we considered another parameter – annual maximum snowline – which is given in the next subsection. From a glaciological viewpoint, aerial changes are more useful on decadal scales than annual basis when considering a long-term global climate change influence.

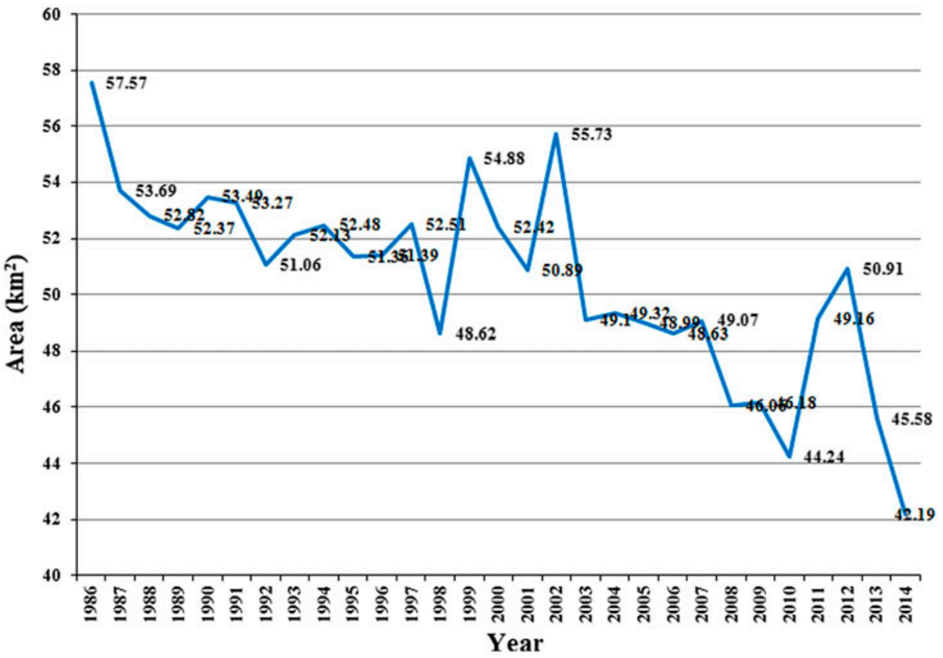

Figure 3. Changes in the annual minimum area of the Nevado Coropuna (1986–2014).

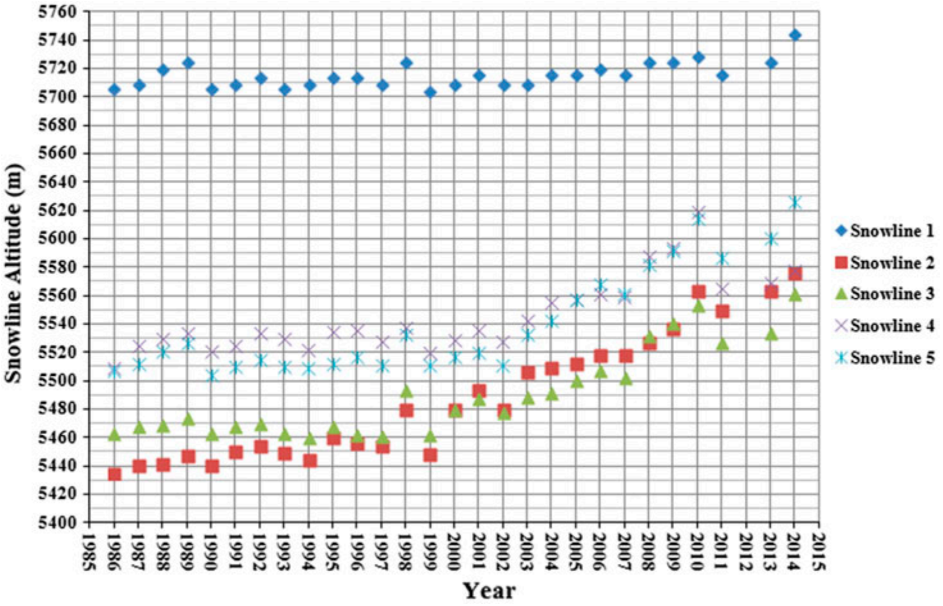

Figure 4. Variations in the annual snowline of selected glaciers (1986–2014).

4.2. Variations in the annual snowline maximum during dry season

The SLA was calculated based on Rabatel et al. (2012). The highest SLA calculated towards the end of dry season (May–September) can be taken as a representative of the ELA (Rabatel et al. 2012), particularly in the outer tropics and the subtropics. Based on comparison and validation with field data on Glaciar Zongo in Bolivia and Glaciar

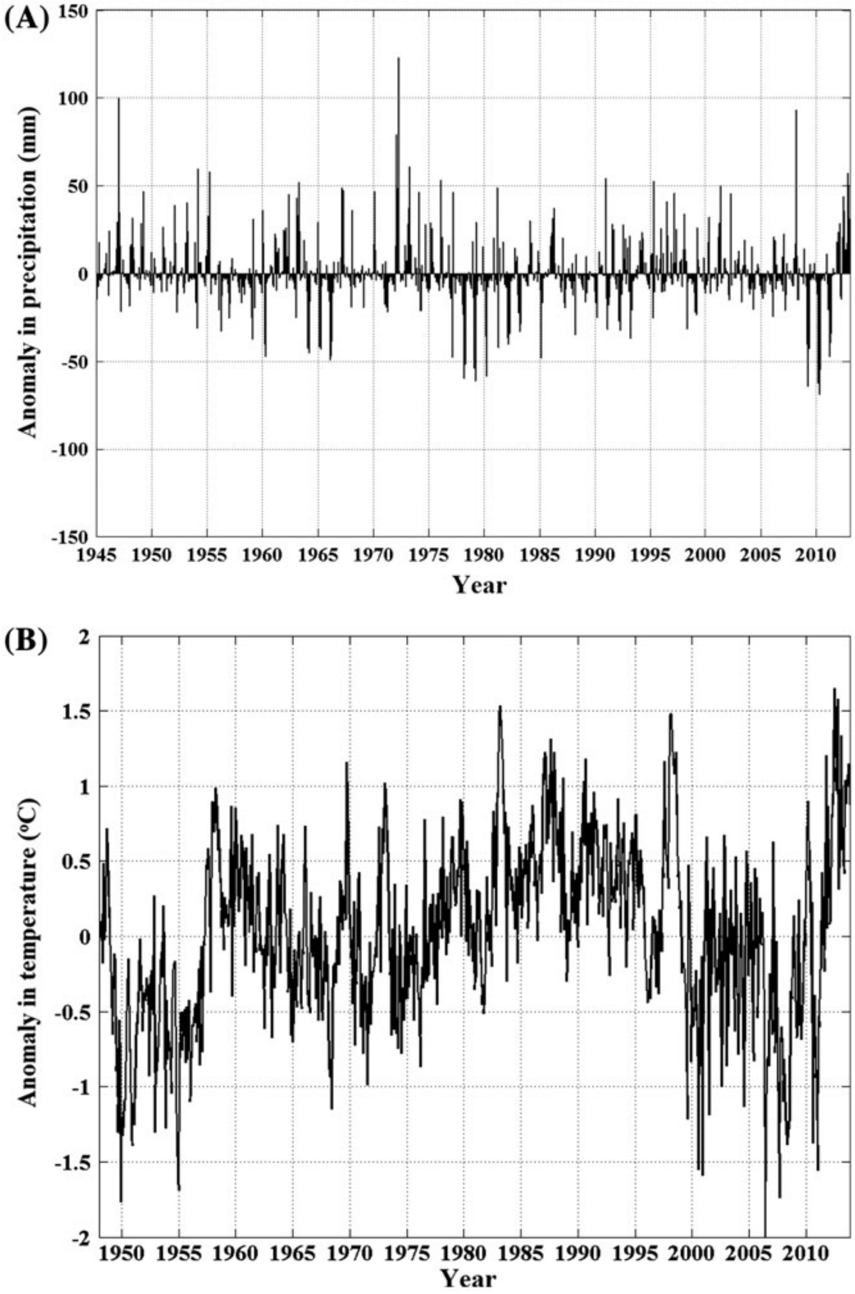

Figure 5. (A) Anomaly in precipitation; (B) Anomaly in temperature.

Artesonraju in Peru, it is found that SLA is a good proxy for ELA and hence can be used to measure annual mass balance changes (Rabatel et al. 2012). In contrast to inner tropics, there is a strong seasonality of precipitation in the outer tropics and hence we can use the maximum SLA during the dry season as a representative of ELA of the year. In order to calculate SLA of the selected glaciers (Figure 1(B)) from Landsat images, 5-4-2 false-colour composite images were created and certain threshold values were applied to TM2 and TM4. The threshold applied to TM4 may vary from 60 to 135 and for TM2, it vary from 80 to 160. The calculated annual snowlines of selected glaciers of the Nevado Coropuna during 1986–2014 are given in Figure 4. It is seen that there was an increasing trend in the SLA during this period and the snowline fluctuations were 'disturbed' with the ENSO and PDO phase changes. It is also seen that the glacier with the highest SLA studied (snowline 1 > 5700 m) showed less fluctuations compared to others due to high altitude, which is normal at higher altitudes due to lower temperature and higher snowfall. The highest snowline may not be at the end of the hydrological year (Rabatel et al. 2012) and it depends on seasonal snowfall, if occurred.

4.3. Calculating the anomalies in precipitation and temperature at the study area

We calculated the anomalies in the precipitation and the temperature near the Neva proven do Coropuna since 1950s using the data-sets from the University of Delaware (Figures 5(A) and (B)). We applied linear interpolation to the gridded data-sets in MATLAB to plot the anomalies. We used only one cell each for temperature and precipitation, which covers the entire study site, to plot the anomaly due to its resolution (0.5° × 0.5° lat-long). We also plotted the ENSO and PDO indices (Figure 6) during 1979–2014 to observe whether the changes in precipitation and temperature at the study site varied with the phase changes of ENSO and PDO. It is noted that a positive regime of PDO has prevailed from the late 1970 to 2008 then started an interrupted cold regime, which is not usual compared to normal patterns of PDO that persists for decades.

A strong correlation between ENSO (and PDO) indices and the calculated anomalies in precipitation is absent in the study region. However, the changes in the annual

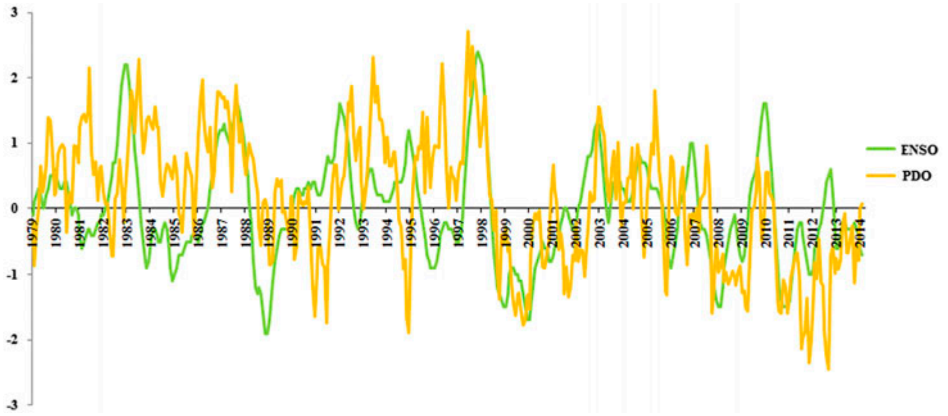

Figure 6. PDO and ENSO indices (1979–2014).

snowline and area of the glaciated region fluctuated heavily with the phase changes of ENSO and PDO and the temperature anomaly has also shown variations during strong ENSO conditions.

5. Discussion

The overall decrease in the glaciated area of the Nevado Coropuna during 1986–2014 (26.92%) is strikingly similar to that during 1962 to 2000 (26%) calculated by Racoviteanu et al. (2007) and this shows that the glaciated area of Nevado Coropuna was decreasing at the rate of about 26% during the last 50 years. Significant glacier recession in the Peruvian Andes started in the mid-nineteenth century itself (Kaser 1999). Some glaciers in the Cordillera Vilcanota in Peru were reported to have lost about 32% of the glacier area during 1962–2006 (Salzmann et al. 2012) and a loss of 35% in the southern part of Cordillera Blanca between 1962 and 1999 is also reported (Mark & Seltzer 2005). Kaser et al. (1996) studied the relationship between the changes in the ELA of Andean glaciers and fluctuations in the climate. However, the presence of excess snow cover on the glacier terminus was always a hindrance for delineating the glacier boundary and ELA using remote sensing data in this region and this problem was later overcome by using ‘snowline’ as a climatic indicator (Arnaud et al. 2001) for this type of glaciers. The presence of distinct dry and wet seasons makes it possible to calculate annual snowline more accurately using satellite images in the outer tropics compared to the inner tropics. Satellite images taken during the end of dry season (May–September) have already proven to be excellent in calculating the annual snowline which in turn can be used as substitute for the ELA based on the case studies on Glaciar Zongo, Bolivia and Glaciar Artesonraju, Peru, by Rabatel et al. (2012). The exceptional increase in the annual snowline and decrease in the surface area of the glacier during 1997–1998, 2004–2005 and 2010 can be well explained by the presence of strong El Niño occurred during the warm regime of PDO. From the results, it is seen that both the glacier area and the snowline did not vary much as expected from the combined influence of the El Niño and the positive PDO occurred during 1991–1995. The possible explanation for this zero or slightly positive mass balance can be explained on the basis of Rabatel et al. (2013) in such a way that the cooling effect of the volcanic sulphate aerosols in the stratosphere due to the eruption of Pinatubo interrupted the influence of the long El Niño during 1991–1995. However, this explanation is difficult to prove statistically.

The influence of ENSO on the ice-covered Nevado Sajama in Bolivia was reported in 2001 (Arnaud et al. 2001), which is located in the CVC where the Nevado Coropuna is also situated. Based on general circulation models (GCM), Minvielle and Garreaud (2011) calculated a significant decrease in the easterly circulation over the Altiplano that may cause a strong decrease in the precipitation in the tropical central Andes towards the end of twenty-first century. Inter-decadal variability in the Andes is associated with long-term changes in the pacific circulation patterns whereas decadal variability is associated with the changes in the circulation patterns over the Amazon basin (Espinoza Villar et al. 2009). Even though many models exist, such as CMIP3, the inconsistent trend in regional precipitation severely limits the understanding of climate changes over the Altiplano (Minvielle & Garreaud 2011). However, it is already understood that the Pacific SST has been increased since the late 1970s because of the so-called Pacific climate shift and this might be one of the causative agents of the observed accelerated glacier retreat (Rabatel et al. 2013). Glaciers situated in different climatic regimes can respond to similar climatic perturbations with different magnitudes (Sagredo & Lowell 2012). In the tropical Andes, this difference in magnitude of response is very visible because the climate is influenced by Atlantic, Pacific and Westerly circulation in varying magnitudes. This magnitude of the influence of the circulation patterns vary from the inner to the outer tropics and results in different MMP and temperature patterns. Altitude is also another important factor that controls the glacier recession in response to climate change (Chevallier et al. 2011). The rate of increase/decrease in the snowline situated at higher altitude (snowline 1) was found to fluctuate less compared to those at a lower altitude (snowline 2 and snowline 3). This is because the higher altitudes in this region are fed by heavy snowfall (note that the maximum precipitation occurs in the summer in low tropical latitudes) whereas rapid ice melting occurs in the lowest parts (Chevallier et al. 2011). At higher altitudes, temperature is also lesser compared to the low-lying glaciers.

Herreros et al. (2009) mentioned that there was no change in the quantity of precipitation in the study area during the strong El Niño during 1997–1998, but glacier mass loss was high from our results. However, by using NCEP-NCAR reanalysis data, Pouyaud (2005) could find a correlation between the runoff from the glaciated drainage basins in the Cordillera Blanca and the air temperature. During the strong El Niño seasons, the temperature values were higher in the Coropuna region as well (Figure 5(B)). There exists a high correlation between the glacier mass loss and air temperature in the mid latitude and high-latitude glaciers (Braithwaite 1981) and this explains how the El Niño events were followed by an elevation in annual snowline. The westerly (dry conditions) and the easterly (wet conditions) are the wind anomalies that are not centred over the central part of Altiplano and the location of these wind anomalies are important in determining the spatial pattern of the precipitation anomalies in the central Andes. A study on three drainage basins (Pacific, Titicaca and Amazonas) in Peru shows that the coastal region is having higher rainfall variability and hence higher runoff variability on seasonal and inter-annual timescales (Lavado Casimiro et al. 2012). It is clear that the increase in the runoff, if exists during low precipitation season, is solely due to accelerated glacier ablation.

6. Conclusions

The Nevado Coropuna in the Cordillera Ampato has lost its 26.92% of total glaciated area during the last three decades (from 57.57 to 42.19 km^2) and this decrease in the area followed the pattern of ENSO, particularly when in phase with PDO. This loss of glaciated area is important because the Peruvian Andes contains about 70% all tropical glaciers in the world. Exceptional cases were found during the prolonged El Niño period during 1991–1995, probably due to the influence of the Pinatubo eruption followed by the cooling effect of aerosols in the stratosphere. The fluctuations in area and annual snowline of this icecap in Peru during the phase changes of ENSO is immediate and higher compared to mountain glaciers in Ecuador or Bolivia and this indicates that glaciers in different climate zone (inner and outer tropics, for example) can show different magnitudes of response to identical climatic perturbation (El Niño, for example). Even though a correlation does not exist between the precipitation anomaly and ENSO in this region, the snowline fluctuations followed the ENSO patterns. It is highly recommended to include the influence of spatial barriers (mountain range) in the study of climate variability in the Andean countries.

Acknowledgements

First author acknowledges Fundação de Amparo à Pesquisa do Estado do Rio Grande do Sul (FAPERGS), Brazil, for his PhD research scholarship and Dr. Walter Silverio, University of Geneva, for the nice MMP graph based on meteorological stations near the study site.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Fundação de Amparo à Pesquisa do Estado do Rio Grande do Sul.

References

Albert TH. 2002. Evaluation of remote sensing techniques for ice-area classification applied to the tropical Quelccaya ice cap, Peru. Polar Geogr. 26:210–226.

Aniya M, Dhakal AS, Park S, Naruse R. 2000. Variations of Patagonian glaciers, South America, using RADARSAT and landsat images. Can J Remote Sens. 26:501–511.

Arnaud Y, Muller F, Vuille M, Ribstein P. 2001. El niño-southern oscillation (ENSO) influence on a Sajama volcano glacier (Bolivia) from 1963 to 1998 as seen from Landsat data and aerial photography. J Geophys Res. 106:773–784.

Bamber JL, Rivera A. 2007. A review of remote sensing methods for glacier mass balance determination. Global Planet Change. 59:138–148.

Braithwaite RJ. 1981. On glacier energy balance, ablation, and air temperature. J Glaciol. 27:381–391.

Bromley GRM, Hall BL, Rademaker KM, Todd CE, Racovteanu A. 2011. Late Pleistocene snowline fluctuations at Nevado Coropuna (15°S), southern Peruvian Andes. J Quat Sci. 26:305–317.

Bromley GRM, Schaefer JM, Winckler G, Hall BL, Todd CE, Rademaker KM. 2009. Relative timing of last glacial maximum and late-glacial events in the central tropical Andes. Quat Sci Rev. 28:2514–2526.

Chevallier P, Pouyaud B, Suarez W, Condom T. 2011. Climate change threats to environment in the tropical Andes: glaciers and water resources. Reg Environ Change. 11:179–187.

Espinoza Villar JC, Ronchail J, Guyot JL, Cochonneau G, Naziano F, Lavado W, De Oliveira E, Pombosa R, Vauchel P. 2009. Spatio-temporal rainfall variability in the Amazon basin countries (Brazil, Peru, Bolivia, Colombia and Ecuador). Int J Climatol. 29:1574–1594.

Garreaud RD. 2009. The Andes climate and weather. Adv Geosci. 22:3–11.

Henderson KA, Thompson L, Lin PN. 1999. Recording of El Niño in ice core δ 18 O records from Nevado Huascarán, Peru. J Geophys Res—Atmos. 104:31053–31065.

Herreros J, Moreno I, Taupin JD, Ginot P, Patris N, De Angelis M, Ledru MP, Delachaux F, Schotterer U. 2009. Environmental records from temperate glacier ice on Nevado Coropuna saddle, southern Peru. Adv Geosci. 22:27–34.

Huh K, Mark BG, Hopkinson C. 2012. Changes of topographic context of the Yanamarey glacier in the tropical Peruvian Andes. Proceedings of the Remote sensing Hydrology symposium, September 2010, Jackson, Wyoming, USA: International Association of Hydrological Sciences, IAHS publications 352, 333–336.

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

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

Lavado-Casimiro WS, Felipe O, Silvestre E, Bourrel L. 2013. ENSO impact on hydrology in Peru. Adv Geosci. 33:33–39.

Lavado Casimiro WS, Ronchail J, Labat D, Espinoza JC, Guyot JL. 2012. Basin-scale analysis of rainfall and runoff in Peru (1969–2004): Pacific, Titicaca and Amazonas drainages. Hydrol Sci J. 57:625–642.

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

Minvielle M, Garreaud R. 2011. Projecting rainfall changes over the South American Altiplano. J Clim. 24:4577–4583.

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

Pope A, Rees G (2014) Using *in situ* spectra to explore Landsat classification of glacier surfaces. Int J Applied Earth Obs Geoinf. 27:42–52.

Pouyaud B. 2005. Devenir des ressources en eau glaciaire de la Cordillère Blanche [Glaciers becoming water resources in the Cordillera Blanca]. Hydrol Sci J. 50:999–1021.

Rabatel A, Bermejo A, Loarte E, Soruco A, Gomez J, Leonardini G, Vincent C, Sicart JE. 2012. Can the snowline be used as an indicator of the equilibrium line and mass balance for glaciers in the outer tropics? J Glaciol. 58:1027–1036.

Rabatel A, Francou B, Soruco A, Gomez J, Cáceres B, Ceballos JL, Basantes R, Vuille M, Sicart JE, Huggel C, et al. 2013. Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. Cryosphere. 7:81–102.

Racoviteanu A, Manley WF, Arnaud Y, Williams MW. 2007. Evaluating digital elevation models for glaciologic applications: an example from Nevado Coropuna, Peruvian Andes. Peruvian Andes Global Planet Change. 59:110–125.

Racoviteanu A, Arnaud Y, Williams MW, Ordoñez J. 2008. Decadal changes in glacier parameters in the Cordillera Blanca, Peru, derived from remote sensing. J Glaciol. 54:499–510.

Sagredo EA, Lowell TV. 2012. Climatology of Andean glaciers: a framework to understand glacier response to climate change. Global Planet Change. 86–87:101–109.

Salzmann N, Huggel C, Calanca P, Díaz A, Jonas T, Jurt C., Konzelmann T, Lagos P, Rohrer M, Silverio W, Zappa M. 2009. Integrated assessment and adaptation to climate change impacts in the Peruvian Andes. Adv Geosci. 22:35–39.

Salzmann N, Huggel C, Rohrer M, Silverio W, Mark BG, Burns P, Portocarrero C. 2012. Glacier changes and climate trends derived from multiple sources in the data scarce Cordillera Vilcanota region, Southern Peruvian Andes. Cryosphere Discuss. 6:387–426.

Sidjak RW, Wheate RD. 1999. Glacier mapping of the Illecillewaet icefield, British Columbia, Canada, using Landsat TM and digital elevation data. I J Remote Sens. 20:273–284.

Silverio W. 2005. Análisis de los parámetros climáticos de las estaciones en la región del Nevado Coropuna (6425 m.s.n.m.), Arequipa, Perú. Informe preparado para la GTZ-Arequipa-PERU (COPASA), en le marco del Proyecto Estudio del Retroceso Glaciar en el Nevado Coropuna, Arequipa, Perú. 16. (internal document)

Thompson LG. 2000. Ice core evidence for climate change in the tropics: implications for our future. Quat Sci Rev. 19:19–35.

Ubeda J. 2011. El impacto del cambio climático en los glaciares del complejo volcánico Nevado Coropuna, Cordillera Occidental de los Andes, [PhD Thesis]. Spain: Universidad Complutense de Madrid.

Veettil BK, Leandro Bayer Maier É, Bremer UF, de Souza SF. 2014. Combined influence of PDO and ENSO on northern Andean glaciers: a case study on the Cotopaxi ice-covered volcano, Ecuador. Clim Dyn. 43:3439–3448.

Vuille M. 2013. Climate change and water resources in the tropical Andes. Inter-American Development Bank (IDB) Technical Note No. IDB-TN-515.

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

Vuille M, Francou B, Wagnon P, Juen I, Kaser G, Mark B, Bradley RS. 2008. Climate change and tropical Andean glaciers: past, present and future. Earth Sci Rev. 89:79–96.

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

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

Wang J, Li W. 2003. Comparison of methods of snow cover mapping by analysing the solar spectrum of satellite remote sensing data in China. Int J Remote Sens. 24:4129–4136.