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ORIGINAL PAPER

Influence of ENSO and PDO on mountain glaciers in the outer tropics: case studies in Bolivia

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Abstract This paper emphasize on the observational investigation of an ice-covered volcano and two glaciated mountains in the Central Andes from 1984 to 2011. Annual snowlines of the Nevado Sajama in the Cordillera Occidental and the Nevado Cololo and the Nevado Huanacuni in the Cordillera Apolobamba in Bolivia were calculated using remote sensing data. Landsat TM, Landsat ETM+, and LISS-III images taken during the end of dry season were used in this study. Changes in the highest annual snowline during May–September is used an indirect measure of the changes in the equilibrium line altitude of the glaciers in the outer tropics. We tried to understand the combined influence of the El Niño-Southern Oscillation and the Pacific Decadal Oscillation on the variations in the annual snowline altitude of the selected glaciers. Meteorological data in the form of gridded datasets were used for calculating the anomalies in precipitation and temperature during the study period. It is found that the glaciated areas were fluctuated with the occurrence of warm and cold phase of ENSO but the magnitude of the influence of ENSO is observed to be controlled by the phase changes of PDO. Snowline of the Nevado Sajama fluctuated heavily when cold and warm phases of ENSO occur during the cold and warm regimes of PDO, respectively. Nevado Cololo and Nevado Huanacuni are showing a continuous retreating trend during the same period. This clearly indicates that the changes in the Pacific SST patterns have more influence on glaciers in the Cordillera Occidental compared with those in the Cordillera Oriental of the Bolivian Andes.

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1 Introduction

Global climate is highly complex and extends over a wide range of spatial scale with a large number of subsystems varying on different timescales. Tropical and subtropical glaciers are extremely sensitive to climate change, and their response to any small imbalances in the environment is relatively rapid (Arnaud et al. 2001). The Andes occupies about 99.7 % of all the tropical glaciers in the world (Kaser 1999). It is predicted that the tropical Andes might experience a massive warming in the order of 4.5–5 °C by the end of twenty-first century and an increase in precipitation during the wet season and a decrease in the same during the dry season (Vuille et al. 2008). Precipitation rates were found to be poorly correlated with rain-induced glacier ablation and runoff, where precipitation is in solid form (Francou et al. 1995). It is found that warming in the upper troposphere in the tropical region is greater than the global mean due to increased latent heat release, and this caused the recent increase in tropical precipitation (Mitchell et al. 1990). With no change in precipitation, an increase in temperature can lead to the disappearance of glacial coverage in the tropics (Rabatel et al. 2013). This can lead to increased shortage of freshwater for domestic and agricultural usage to a majority of population, particularly in Peru and Bolivia, due to the reduction in quantity of meltwater originating from glaciers.

The Andes in South America is passing through a large number of temperature and precipitation zones with higher

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influence of Atlantic circulation patterns in the north and Pacific influence in the south (Sagredo and Lowell 2012). Both circulation patterns influence the central Andean region. Easterly wind anomalies favor wet conditions in the central Andes whereas westerly wind enhances dry conditions (Vuille and Keimig 2004). Some of the glaciers in Bolivia, such as Glacier Charquini, lost about 65–78 % of its little ice age (LIA) surface area, and the equilibrium line have been increased by 160 m (Rabatel et al. 2006). Interannual variability and longer-term trends in mass balance changes of larger and smaller glaciers were found to be very similar (Vuille et al. 2008). Even though many climate models exist that predict the future changes of the tropical glaciers, many of them ignore the changes in the ocean (salinity, for example) and ocean circulations that contributes El Niño-Southern Oscillation (ENSO) and other decadal oscillations that influences the present distribution and frequency of tropical storms. ENSO events are associated with drought in the Altiplano, which favors glacier melting and retard runoff in the non-glaciated areas (Ribstein et al. 1995). ENSO events are characterized by a markedly negative mass balance with a water depletion equivalent to twice the amount of the accumulated precipitation, an elevation in the equilibrium line altitude (ELA), a reduction in the accumulation-area ratio (AAR), and a substantially reduced accumulation rate at high altitude. A decrease in the glacier accumulation with the warm phase of ENSO was confirmed based on the studies on the Quelccaya ice cap in Peru (Thompson et al. 1984) and also based on the analysis of water records from Glaciar Zongo in Bolivia (Ribstein et al. 1995). ENSO controls majority of the interannual variability of mass balance at a regional scale in the Cordillera Real (Rabatel et al. 2006). However, correlating these effects just with short-lived ENSO events does not seem to be promising. Recent studies suggest a combined effect of ENSO with a long-lived, ENSO like, Pacific Decadal Oscillation (PDO) on tropical climate (Kim et al. 2014; Veettil et al. 2014). Other southern hemisphere oscillations like Antarctic Oscillation (AAO), which is the counterpart of Arctic Oscillation (AO) in the northern hemisphere, could be considered while studying the influence of complex circulation anomalies in the tropical South America. Atlantic sea surface temperature (SST) variability cannot be considered as completely independent on the Pacific SST variability (Enfield and Mayer 1997), particularly during the boreal spring. By considering the combined effects of all these phenomena, we might be able to explain the influence of climate variations on tropical Andean glaciers that were not or least explained based only on the ENSO.

Even though sometimes limited by spatial, spectral, and temporal properties, recent advances in remote sensing and photogrammetric techniques helped the scientific community to understand recent surface and mass balance changes, and to study the evolution of tropical mountain glaciers, at least from the mid-twentieth century. Many researchers (Arnaud et al. 2001; Rabatel et al. 2012) used remotely sensed images and digital elevation models (DEM) to calculate the snowline altitude (SLA) that can be used to calculate an approximate value of the ELA in the outer tropics. This ELA can be used to calculate the approximate mass balance change, which in turn helps to understand the climate dynamics in the tropical Andes. In this study, we tried to explore the possibility of using the annual snowline maximum of glaciers in the western and eastern cordilleras of the Bolivian Andes as an equivalent of the ELA and attempted to correlate the snowline variations with the anomalies in monthly precipitation and temperature. We also tried to find if any teleconnection exists between the glacier variations and the occurrences of ENSO, PDO, and AAO.

2 Study sites and climate conditions

Bolivia is considered as a tropical country with its main altitudinal divisions consisting of the lowlands (<800 m above sea level (ASL)), the Andean slopes (800–3200 m ASL), and the highlands or the Altiplano (>3200–6500 m ASL) (Fig. 1a). Climate in Bolivia varies from tropical to cold desert climate depending on the altitude (Seiler et al. 2013a). Annual mean surface air temperatures vary from 0 to 30 °C, and precipitation ranges from less than 300 to 3000 mm per year. Precipitation in Bolivia and its interannual variability is linked to the tropical SST anomalies and atmospheric circulation patterns (Arnaud et al. 2001; Vuille, 1999). Majority of the precipitation occurs during December–March, and the austral summer (DJF) is characterized by a low-pressure system that enhances easterly trade winds to transport moisture from the Atlantic (northern tropics) to the continent. This moisture content, which is deflected by the Andes, is transported towards the south and causes enhanced precipitation in the Atlantic Ocean. Condensational heat release over the Amazon occurs simultaneously, and the Andean slopes cause the formation of an upper-level Bolivian high-pressure system, which causes enhanced transport of moisture from the Amazon to the Bolivian highlands and lowlands (Seiler et al. 2013a; Vuille 1999). In the austral winter (JJA), less moisture transport occurs from the northern tropical Atlantic to the continent and the cold fronts from the South Pole penetrate into the Bolivian lowlands thereby lowering the temperature and limit the precipitation (Garreaud 2009). The prevailing westerly winds in Bolivia prevent moisture transport to the Andes during the austral winter (Vuille 1999). Three main sources of climate variability in Bolivia are the Pacific decadal oscillation, El Niño-Southern Oscillation, and Antarctic Oscillation (Seiler et al. 2013b).

Glaciers in Bolivia are situated in two mountain ranges in the outer tropics—Cordillera Occidental along the western

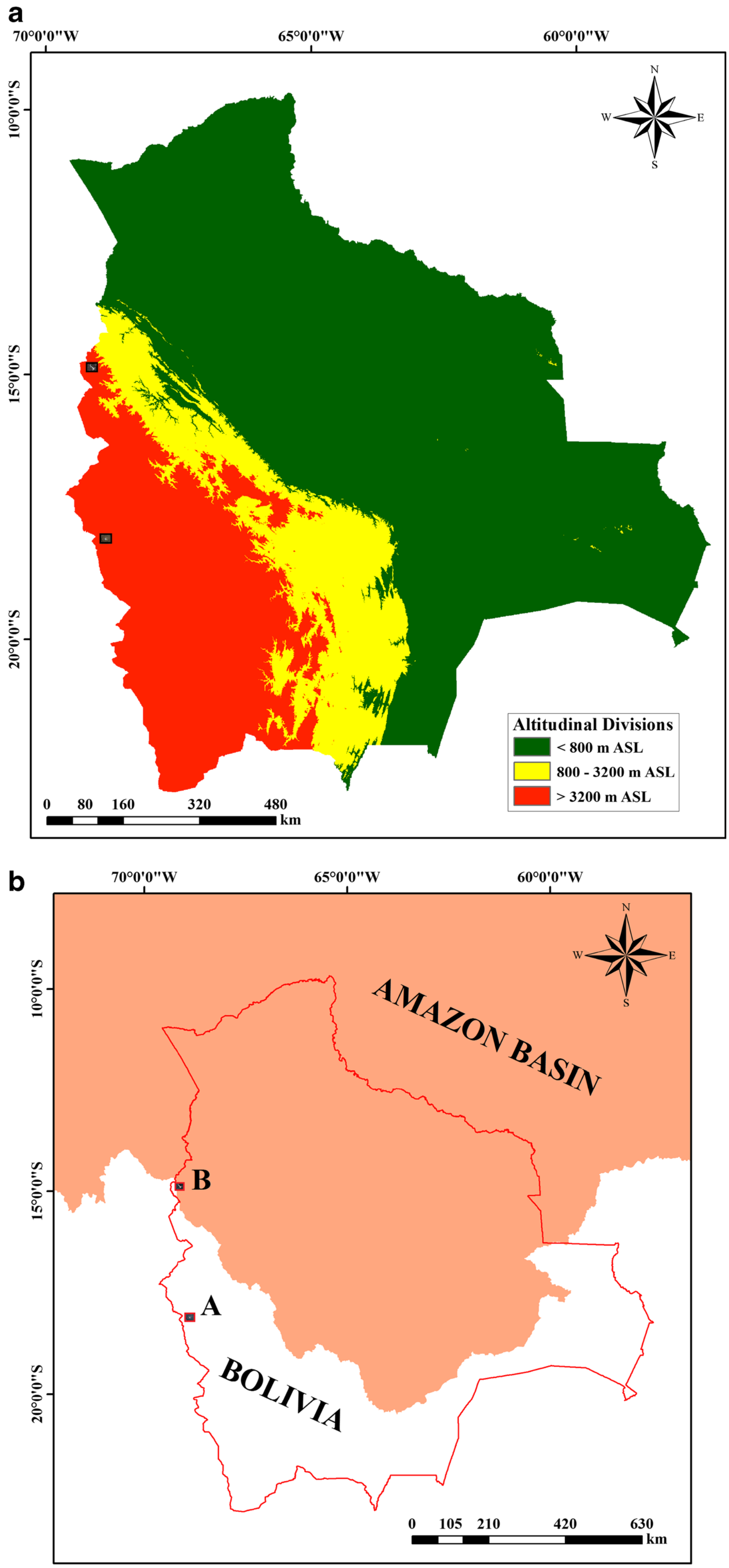

Fig. 1 **a** Altitudinal divisions in Bolivia. **b** Relative locations of the study sites (*A* Sajama, *B* Cololo and Huanacuni) with the Amazon basin

border with the Chile and the Cordilleras Apolobamba, Real, Tres Cruces and Nevado Santa Vera Cruz in the east (Vuille et al. 2008). Glaciers in the Cordillera Real such as Nevado Illimani were studied extensively by many researchers using ice core records and remote sensing (Ramirez et al. 2003; Ribeiro et al. 2013). Figure 1b shows the relative locations of the two study sites (A. Nevado Sajama, B. Nevado Cololo and Nevado Huanacuni) considered in this research with the Amazon Basin. Sajama ice-covered volcano (18° 06′ S, 68° 50′ W, 6542 m ASL) in the Oruro Department, Sajama Province in Bolivia is a stratovolcano in the Central Volcanic Zone (CVZ) in the Central Andes and is the highest peak in Bolivia and the southernmost ice-cap in the intertropical zone. Nevado Cololo (14° 50′ S, 69° 06′ W, 5859 m ASL) and the nearest Nevado Huanacuni (5058 m asl) in the Cordillera Apolobamba are separated from the Cordillera Occidental by the Altiplano is the other study site considered in this study. By using Landsat images, Oliveira (2013) observed that the Cololo-Huanacuni complex is currently not having any glaciers below 4626 m ASL whereas in 1975, the lowest glacier terminus observed was about 4317 m ASL.

Monthly mean precipitation rate is having high longitudinal gradient from west to east, and hence, the observed precipitation is very different in the two cordilleras in Bolivia. Precipitation occurs by the mechanism of Amazonian monsoon that causes about 80 % of the annual precipitation from October to April, particularly in the Cordillera Real (Rabatel et al. 2006). In the Sajama and Cololo regions, monthly precipitation pattern is similar but varies quantitatively (Fig. 2). It is also visible that the precipitation patterns are different during May–July. This means that there is a latitudinal gradient in precipitation from one study site to the other (Nevado Sajama is close to the Pacific as well as the subtropics). Higher precipitation rate occurred near the Nevado Cololo is due to the enhanced moisture content transported by the atmospheric circulation from the Amazon Basin. This process seems to be weakening towards the Nevado Sajama.

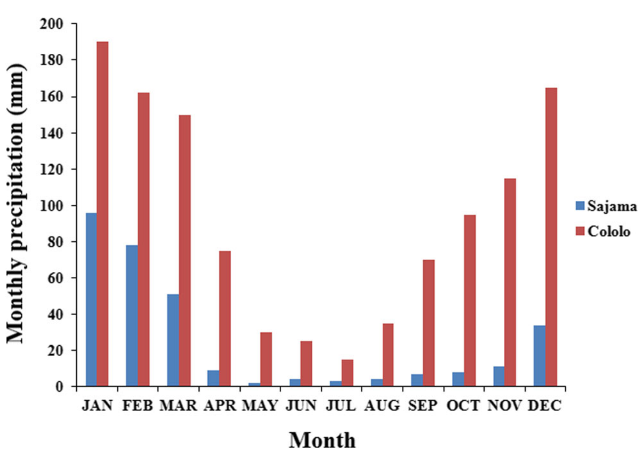

Fig. 2 Difference in the mean monthly precipitation (in mm) near the study locations in the two cordilleras in Bolivia

3 Datasets

Both remote sensing and meteorological datasets were used in this study. The remote sensing data includes multispectral images and digital elevation models from various sensors. The meteorological data includes temperature and precipitation data obtained from various sources. The second type also includes the three indices—ENSO, PDO, and AAO. The following subsections describe the datasets used and their suitability in this research.

3.1 Satellite data

A large number of research papers are available on the measurement of physical and surface characteristics of glaciers including snowline position and altitude, surface elevation, and terminus position based on remote sensing and photogrammetry (Arnaud et al. 2001; Bamber and Rivera 2007; Rabatel et al. 2012; Veettil et al. 2014). Satellite images are available since 1972 from Landsat series (MSS, TM, ETM+, and LDCM). Multisource image data including Landsat TM, ETM+, and IRS LISS III taken during the austral winter (May–August) were used in this research. During this time, ablation will be least and the glacier terminus would not be covered with fresh snow. Landsat TM and ETM+ images are having a spatial resolution of 30 m in visible and infrared channels. Spatial resolution of thermal channel in Landsat TM is 120 m and that in ETM+ is 60 m. A panchromatic channel (15 m) is also present in ETM+. LISS III is a multispectral camera operating in four spectral bands, three in the visible and near-infrared (VNIR) and one in the shortwave infrared (SWIR), each with a spatial resolution of 23.5 m. Spectral coverage of the images used here is given in Table 1. Only cloud-free images were used in order to avoid the difficulty in delineation of ice margin. Other than

Table 1 Spectral coverage of the images used

Channel	Spectral range (μm)		
	Landsat TM	Landsat ETM+	IRS LISS III
Blue (TM1)	0.450–0.520	0.450–0.515	
Green (TM2)	0.520–0.600	0.525–0.605	0.520–0.590
Red (TM3)	0.630–0.690	0.630–0.690	0.620–0.680
NIR (TM4)	0.760–0.900	0.775–0.900	0.770–0.860
SWIR1 (TM5)	1.550–1.750	1.550–1.750	1.550–1.700
Thermal IR (TM6)	10.40–12.50	10.40–12.50	
SWIR2 (TM7)	2.080–2.350	2.090–2.350	

multispectral images, DEMs from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Models (GDEM) were also used in this research. The DEMs used were having a spatial resolution of 30 m and a vertical accuracy of 20 m which is suitable for the selected glaciers for the study due to comparable slopes. Co-registration of the images with DEMs and atmospheric correction using MODTRAN were done before applying other image processing algorithms. Image processing steps were done using Erdas Imagine and ESRI ArcGIS 10.1 software packages. Landsat TM image subsets (false color composites) of the study sites and the selected glaciers considered in this research are given in Fig. 3.

3.2 Meteorological data

High resolution, gridded, monthly precipitation and temperature (above 2 m from the ground level) data with a horizontal resolution of 0.5° lat-long during a period of 1948 to 2008 from the University of Delaware is used in this research (http://www.esrl.noaa.gov/psd/data/gridded/data.UDel_AirT_Precip.html). These data were derived from a large number of stations including Global Historical Climate Network (GHCN2) and archives of Legates and Willmott (Legates and Willmott 1990). Even though the precipitation and temperature data were derived from various existing meteorological stations, it is not totally free from errors. In mountainous environments, installation of meteorological stations is not always possible and the presence of altitudinal gradient in precipitation and surface temperature can also contribute some errors. Ocean Niño Index (ONI) and AAO index were downloaded from Climate Prediction Center (CPC), National Oceanic and Atmospheric Administration (NOAA) (http://www.cpc.ncep.noaa.gov). In this data, cold and warm episodes were defined when a threshold of ±0.5 °C is met for a minimum of five consecutive overlapping seasons. Pacific Decadal Oscillation (PDO), an index based on the variations in SST in the north Pacific, is downloaded from Joint Institute for the Study of the Atmosphere and Ocean (JISAO) (http://jisao.washington.edu/data_sets/pdo/).

4 Methodology and results

Image processing and meteorological data analysis were the two step processes done in this research. Image processing is used to calculate the snowline altitudes. Length (horizontal) changes in the terminus are not considered here because in the accumulation area it may or may not represent a change in the mass balance (Bamber and Rivera 2007). Many researchers studied the response of ELA to climatic variations in the Andes and Alps (Arnaud et al. 2001; Rabatel et al. 2012; Veettil et al. 2014). ELA separates the accumulation (positive mass balance) zone from the ablation (negative mass balance) zone and hence is a good proxy for monitoring mass balance changes. The highest SLA detected using satellite imagery during the dry austral winter can be considered as an equivalent to estimate the equilibrium line altitude of the year (Rabatel et al. 2012).

4.1 Calculation of snowline altitudes

Landsat TM3/TM5 and TM4/TM5 band ratio images (Bolch and Kamp, 2006) were widely used to distinguish "clean" glaciers from other land surface features by applying a suitable threshold to the ratio image, though ratio images are sensitive to the influence from thin clouds. Normalized Difference Snow Index (NDSI = [TM2 – TM5] / [TM2 + TM5]) is excellent for the spectral discrimination of snow and other surface features like soil, rock, dust, and water and is also proved to be suitable for snow cover mapping in rough topography (Silverio and Jaquet 2005). Even though band ratios and NDSI can be used to discriminate the spectral characteristics of snow and ice, it is still inadequate to calculate the snowline, particularly when the terminus is covered with fresh snow or a continuous ablation occurs throughout the year. Therefore, we did not adopt band ratios or NDSI methods in this research. Rabatel et al. (2012) adopted another methodology to calculate SLA using a Landsat 5-4-2 false-color composite image that can be used to get a more accurate value of the ELA and is followed in this study. In this method, TM4 (IRS 3) and TM2 (IRS 1) channels were applied with threshold values of 60 to 135 and 80 to 160 respectively before creating the 5-4-2 composite image to map the SLA successfully (4-3-1 for LISS III image). On interannual scales, when dealing with long-term climate influence, changes in the area of glaciers are not so useful compared to the equilibrium line or mass balance changes (Veettil et al. 2015) and hence not is used as a parameter in this study. While using remote sensing techniques, it is difficult to calculate error in the calculation of SLA and it depends on the image coregistration error in relation to the horizontal and vertical DEM resolution as well as depends on the terrain slope (Arnaud et al. 2001). Glaciers selected for calculating the snowline were free from shadow effects and were having lower slopes. However, the same method can be applied when shadow effects or steep terrain are present by using a suitable topographic correction.

The results of the SLA calculations at Nevado Sajama in the Cordillera Occidental and Nevado Cololo and Nevado Huanacuni in the Cordillera Apolobamba are summarized in Fig. 4. From the calculated values of SLAs during the study period, Nevado Sajama is found to have fluctuated heavily when cold and warm phases of ENSO occurs during the cold and warm regimes respectively of PDO (described in subsection 4.3). Apart from higher rates of precipitation, Nevado Cololo and Nevado Huanacuni also fluctuated in a

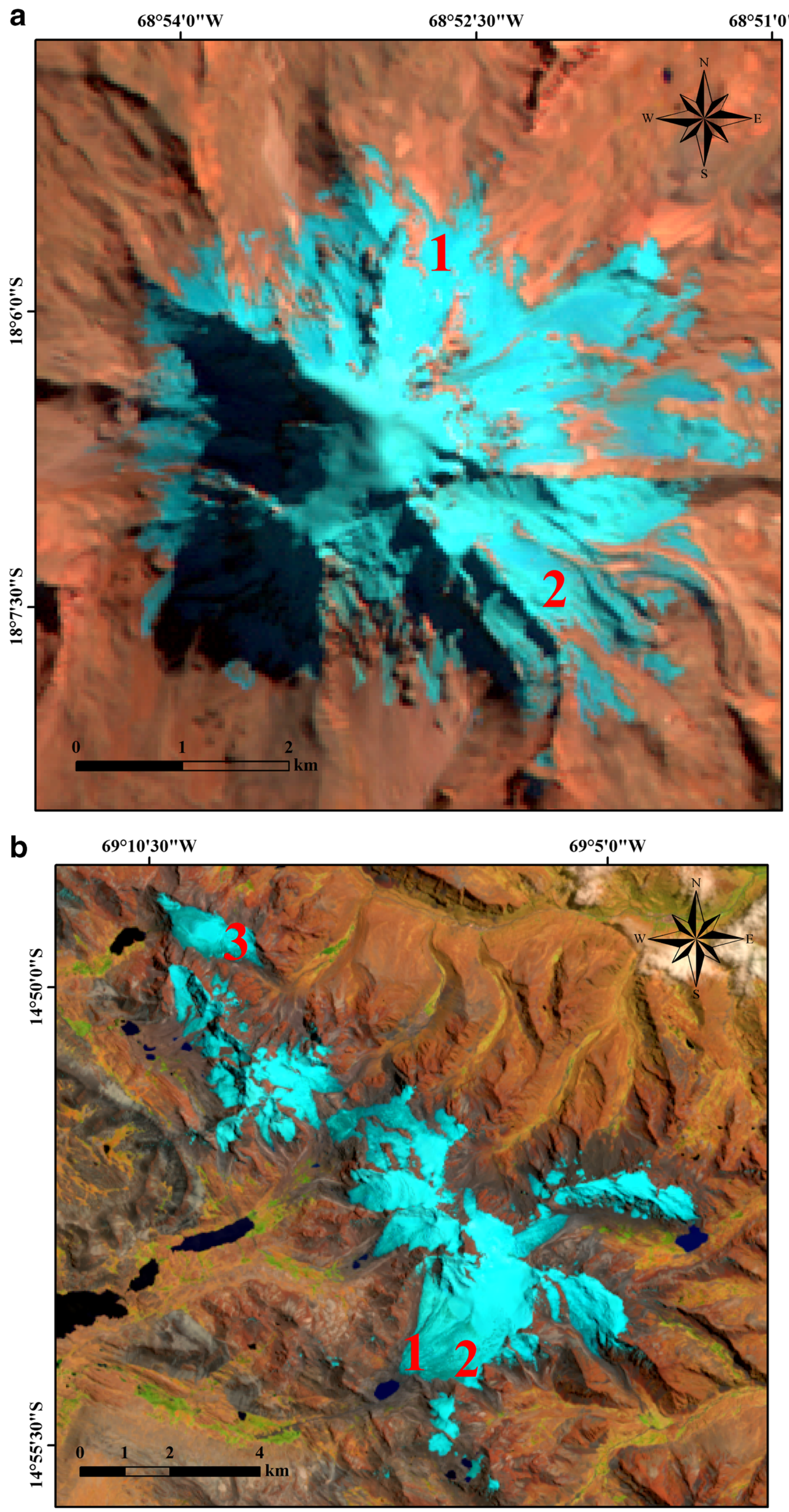

Fig. 3 Landsat false color composite image subsets of the study sites and their selected glacier outlets to calculate snowline altitudes of the study sites **a** Nevado Sajama and **b** Nevado Cololo (glacier outlets 1 and 2) and Nevado Huanacuni (outlet 3)

similar manner but the rate of recession in this region is higher. It is interesting to note that the response of SLAs with ENSO and PDO is higher in Bolivia, compared to that in Ecuador as calculated by Veettil et al. (2014). The possible reasons are as follows: (1) Bolivian glaciers are subjected to increased fluctuations in SLAs with SST variations compared to the

Ecuadorian glaciers or (2) errors in the calculation of SLAs in the case of Ecuadorian glaciers were interfered due to the absence of a unique precipitation season. These two possibilities are considered in the discussion section. In this research, we considered two geometrical parameters as well—glacier altitude and exposure. As observed from Fig. 4a, b, different glacier outlets of the same region showed similar retreating trend. However, there exists a small difference in the behavior of glacier outlet 3 (Nevado Huanacuni) in the second study site, and this can be due to the altitudinal differences. It is known that glaciers at lower altitudes are less resistant to mass loss (except sublimation) compared to those at higher

Fig. 4 Variations in the SLA (in meters) from 1984 to 2013. **a** Sajama and **b** Cololo and Huanacuni

altitudes, particularly in the lower and mid latitudes. This is visible in the case on glacier outlet 2 of Nevado Sajama during 2003–2007, when the glacier outlet 1 that is having a higher altitude has lowered its snowline during this period. Despite of altitudinal differences, snowlines of selected glaciers at same geographical locations varied in a nearly similar way.

4.2 Anomalies in precipitation and temperature in the study sites

We analyzed the anomalies in the monthly precipitation and temperature in the Cordillera Occidental and Cordillera Apolobamba in a similar way as described in Veettil et al. (2014) using the gridded datasets (1945–present) from the University of Delaware by applying linear interpolation in MATLAB. One cell each of the gridded datasets was used to calculate the anomalies for the two study sites. The weaker precipitation rate near the Nevado Sajama is clearly visible from Fig. 5a compared to that near the Nevado Cololo (Fig. 5b). The major precipitation source in the Central Andes is the moist air transported from the Amazon Basin. Accordingly, precipitation rate within the Amazon Basin is expected to be more in the eastern parts of the Altiplano than the western region and is visible from the Fig. 5a, b. During El Niño, moisture advection towards the Pacific is lowered, and this region is more sensitive to ENSO-induced circulation anomalies. Moreover, rapid fluctuations in the magnitudes of precipitation anomaly were observed at Sajama, and it is hypothesized that this geographic location is highly influenced by the changes in the Pacific SST. Note that this region is within 150 km from the Pacific coast. Unlike the anomalies in precipitation, temperature anomalies (Fig. 5c, d) are showing closely related patterns in the two study sites. It is seen that, in spite of the fact that the Sajama region is having a higher altitude, higher temperature anomalies were experienced during the strong El Niño period (during 1997–1998, for example). This shows that glaciers near the Pacific coast (in the western cordillera) might undergo fluctuations in ELA (and hence mass balance) with Pacific SST variations rapidly compared with glaciers in the Cordillera Apolobamba.

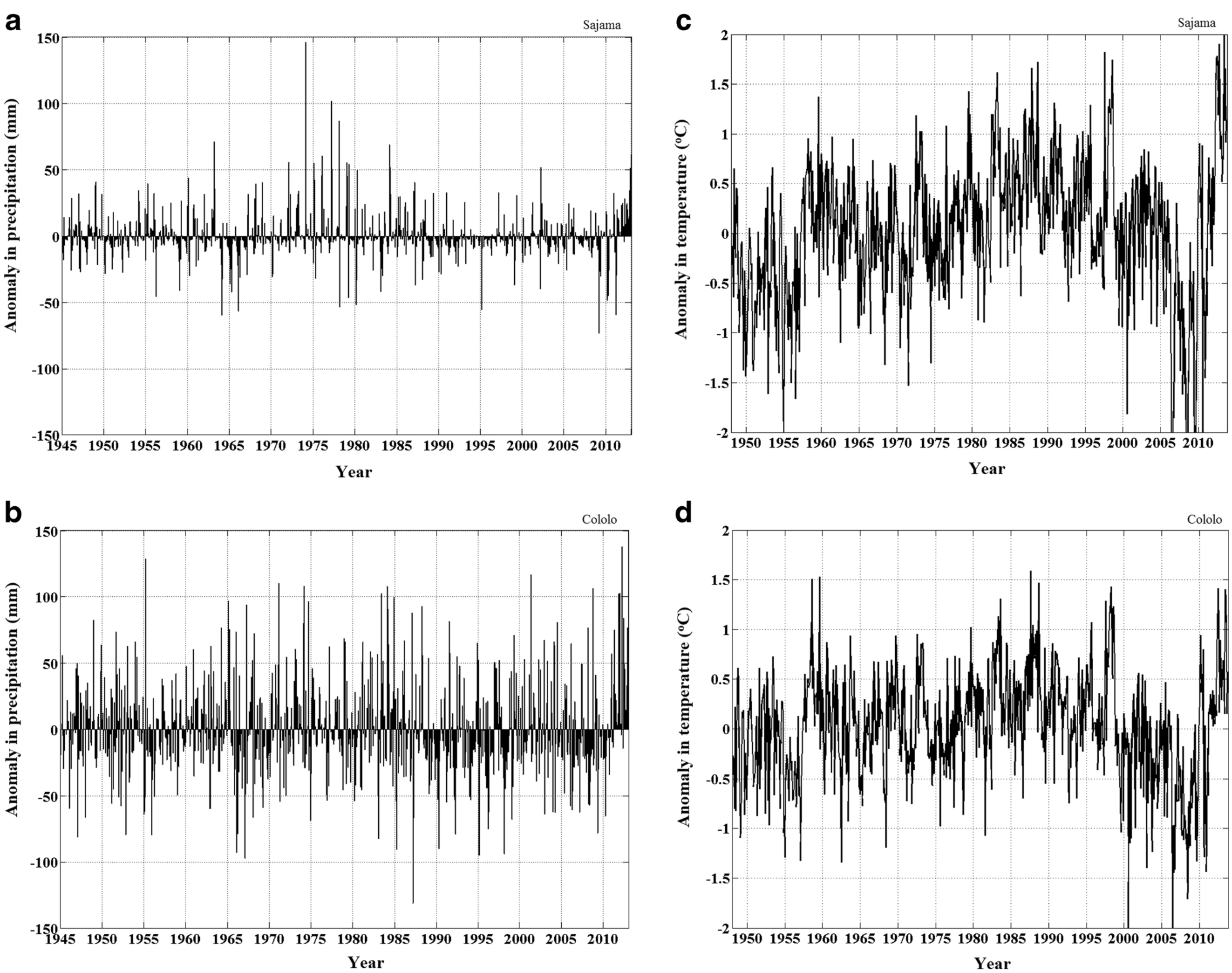

Fig. 5 Anomalies in precipitation (**a** Sajama and **b** Cololo) and temperature (**c** Sajama and **d** Cololo)

4.3 Considering the three sources of climate variability in Bolivia—ENSO, PDO, and AAO

We considered three sources of climate variability in Bolivia—ENSO, PDO, and AAO. A positive correlation between El Niño and PDO is observed, and El Niño-related precipitation anomalies were found to be stronger during the warm phases of PDO (Garreaud et al. 2009). Such a combination would influence the precipitation, if no changes in temperature occur throughout the year (which is common in the tropics), and snowline of the glaciers in this region might fluctuate accordingly. El Niño and La Niña events were known to affect the natural systems and economy in Bolivia for a long time. In this research, we considered the Antarctic Oscillation (AAO) as well, to investigate any connections existing between the positive and negative phases of AAO with the calculated changes in the snowline altitudes. AAO was observed to be causing tropospheric circulation variability towards the south of 20° S (Thompson and Wallace 2000). The geographical locations of the study sites, comparison to mountain glaciers in the inner tropics, are near to 20° S (Sajama, 18° S; Cololo, 14° S), and this justifies the inclusion of AAO in this study. The graphical representation of ENSO, PDO, and AAO indices are given in Fig. 6.

El Niño episodes are associated with below normal precipitation and warmer than normal conditions in the tropical region of the Andes. However, above normal precipitation is observed towards the southeastern region during El Niño conditions (Garreaud et al. 2009). The positive correlation between ENSO and temperature maximize during December–March (Garreaud et al. 2009) and the calculation of snowline during May–August is suitable because there is a lag of 1–3 months to occur an atmospheric response to ENSO in the continent (Kumar and Hoerling 2003). Moreover, the calculated snowline during this period gives a more accurate approximation of the ELA (Rabatel et al. 2012). The absence of seasonal snow and low ablation at the terminus during this period make it an easy task to calculate the snowline using satellite images. However, the influence of ENSO can be altered further due to other factors (strong westerly, for example) prevailing in the continent. Hence, it is difficult to establish a direct correlation between ENSO and PDO with the changes in snowline rather than observational investigation. Only a few station data are available, and this limits the calculation of interdecadal changes and spatial patterns of PDO, which is a long-lived pattern of pacific climate variability and shifts its regime in many decades. Even though there are signals of combined influence of ENSO and PDO on glaciers in the inner tropics (Veettil et al. 2014), the link between both stays unclear (Newman et al. 2003). Higher positive anomalies in precipitation are observed before 1980, before the PDO entered its recent positive regime until 2008. The influence of AAO is, however, visible significantly below 40° S (Gillett et al. 2006).

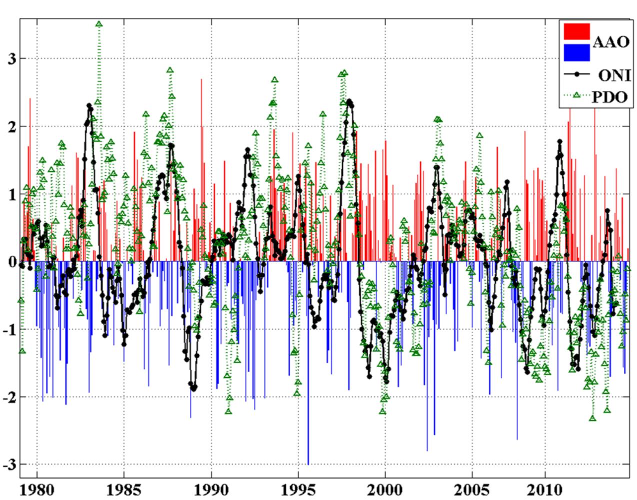

Fig. 6 ENSO, PDO, and AAO indices

5 Discussion

Glaciers in different climatic conditions respond to similar climatic perturbations differently (Sagredo and Lowell 2012). In a warming climate, a high wintertime temperature can accelerate glacier ablation (Bonanno et al. 2013). Kaser and Osmaston (2002) proposed that if the location of a glacier is above the mean annual 0 °C isotherm, it would be highly sensitive to precipitation variability and insensitive to temperature variability. Summer accumulation glaciers are more sensitive to temperature variability than those with winter-accumulating ones (Fujita 2008). Larger surface mass balance variability found in the case of Zongo glacier in Bolivia shows the vulnerability of low-lying glaciers during the recent decades (Soruco et al. 2009). In a warming environment, when no change in precipitation occurs, smaller glaciers in the lower altitudes disappear faster (Chevallier et al. 2011) due to the lowering of accumulation/ablation ratio. It is reported that glaciers in Bolivia have been retreated rapidly between 1975 and 1983, and again between 1997 and 2006 (Soruco 2008), and this research confirms this finding. Periods of stability in the mass balance were observed during 1956–1975 (PDO cold regime) and 1992–1996 (unexpected). Similar trends were observed in the case of Antizana 15 (Francou et al. 2000, 2003) and Cotopaxi (Veettil et al. 2014) in the Ecuadorian Andes. In the case of Ecuador, the calculation of SLA which is close to ELA of the year is difficult to obtain due to the absence of a specific precipitation season, and this might cause additional errors in calculating the SLA along with the discrepancies in the remote sensing data. However, it is found that a rapid retreat has occurred in the case of Nevado Cololo, when compared with glaciers in Ecuador. Inner tropics are found to be getting cloudier and wetter than the outer tropics that are getting drier (Vuille et al. 2008). Snowline of Nevado Sajama fluctuated with the occurrence of ENSO (in phase with PDO) events, whereas the snowlines of Nevado Cololo and Nevado Huanacuni showed a (nearly) continuous increasing trend. The elevation in the snowline during the El Niño episodes during 1991–1995 must be evaluated carefully. There was a rapid increase in the snowline during 1991–1992 (Fig. 4a, b). This snowline did not vary much during 1992–1995 even though the El Niño events were stronger and prolonged. One of the possible reasons behind this anomaly can be the cooling effect of the volcanic aerosols in the stratosphere due to the eruption of Mount Pinatubo on June 15, 1991 (Rabatel et al. 2013).

Glaciers in the tropics are having two special features—these are subjected to higher levels of energy forcing due to the specific latitudinal and altitudinal location; and accumulation and ablation occurs simultaneously (this equilibrium can be broken by climate imbalances) due to year-round precipitation (Chevallier et al. 2011; Kaser and Osmaston 2002). The influence of ENSO and other ocean-atmospheric phenomena on the Andean climate varies along its length (Garreaud 2009). In the outer tropics, the annual distribution of precipitation, particularly during December–February, influences the annual melting (Favier et al. 2004). However, the precipitation variations take a longer time to affect the glacier terminus in comparison with temperature fluctuations (Bonanno et al. 2013). Many researchers (Raper and Braithwaite 2006; Rupper and Roe 2008) suggest that the glaciers in wet climate are more sensitive to temperature rise than in a dry climate. Main moisture source for precipitation in the Altiplano is transported from the eastern lowlands of the Andes, which is highly dependent on the tropical SST anomalies (Vuille et al. 2000). El Niño events induce precipitation deficits in the outer tropics, which in turn promotes glacier melting. In the inner tropics, temperature increase associated with warm phases of ENSO events causes augmented melt rates. Moreover, rate of liquid precipitation is higher in the inner tropics whereas solid precipitation is almost absent, which is common in the outer tropics (Favier et al. 2004). Other than altitudinal variations, the rate of glacier mass loss in the tropical Andes is highly dependent on the geometric characteristics such as exposure. Glaciers oriented towards east and south were found to have lesser retreat compared with those oriented towards the north and west (Soruco et al. 2009). The slight mass gained by these glaciers during 1963–1975 can be explained by the predominant cold regime of PDO during 1962–1976 (Veettil et al. 2014). It is seen that there is an imbalance in the frequency of occurrences of PDO after 1998–1999. Warm phases of PDO are observed to be dominating recently until 2007.

ENSO phase changes can have an important role in modulating the AAO phases (Carvalho et al. 2005). Even though most of the studies pointed out that AAO has its significant effects on the extratropical climate (Carvalho et al. 2005; Pohl et al. 2010), a recent study (Gong et al. 2009) has pointed out that there are signatures of AO and AAO in the tropical coral proxies over the South China Sea. Antarctic climate changes are neither totally independent on Pacific SST variations nor a regional issue (Carvalho et al. 2005). AAO is one of the causes of atmospheric variability in the southern hemisphere up to higher latitudes (20° S) (Pohl et al. 2010), and ENSO affects stratospheric circulation variations, both in the tropics and poles (Hurwitz et al. 2011). It is seen (Carvalho et al. 2005) that majority of the positive AAO conditions were associated with a negative ENSO (La Niña) events and vice-versa, which shows that there are some interrelations between ENSO and AAO. But other than ENSO and its combined mode with PDO, no significant influence was observed on the snowline variations due to the phase changes of AAO. However, further studies are needed for clarification. It might be interesting to investigate whether the occurrence of a positive phase of AAO is to recover the combined warming effects of ENSO and PDO.

Inter-annual variability of the mass balance at the study sites are highly dependent on the inter-annual variability of the precipitation during the summer (Favier et al. 2004) and the interannual precipitation variability is highly dependent on the atmospheric circulation anomalies during the extreme phases of Southern Oscillation (Vuille et al. 2000). Sometimes, a snow-cover of higher albedo is enough to prevent the rapid ablation during the time of weak precipitation (Soruco et al. 2009). Precipitation and air temperature are the determining factors in the SLA changes in the outer tropics. Precipitation and temperature at the study sites were highly influenced by ENSO due to the reduction in the advection of moist air from the continent due to powerful mid-level westerlies (Vuille 1999; Vuille et al. 2000; Garreaud and Aceituno 2001). Due to low spatial resolution of the precipitation datasets, correlation between ENSO and precipitation variability was not established in this research. Moreover, installation of meteorological stations at very high altitudes is nearly impossible, and this would add some errors to the calculated anomalies in precipitation and temperature from gridded datasets with a resolution of 0.5 × 0.5°. Precipitation near the Nevado Sajama is highly influenced by the large-scale circulation changes over the Altiplano (Vuille 1999). Correlation between the ENSO and the precipitation in the Altiplano is reported to be highest during December-January-February (Garreaud et al. 2009). During the occurrences of the El Niño, westerly wind anomalies prevent the transportation of moisture from the eastern continent into the Sajama region (Vuille 1999). In the case of Nevado Cololo, a higher monthly precipitation occurs (Fig. 2) due to the moist air transport from the Amazon Basin. It is known that dry and cold conditions prevail along the pacific coast, and relatively warm and humid conditions prevail in the continent (Garreaud 2009). Due to this dry and cold condition near the Nevado

Sajama, variation in its SLA is not as rapid as the case of Nevado Cololo. In addition, western side of the Altiplano is more sensitive to ENSO than the eastern region (Vuille et al. 2000). Walker circulation is one of the defining features of tropical climate—a stronger Walker circulation implies a La Niña condition and a weaker one implies an El Niño condition. Ice core records from Quelccaya ice cap in Peru suggest that a rise in temperature has occurred during the twentieth century (Thompson et al. 1984), even though the changes in precipitation are not so visible (Vuille et al. 2008). Even though there is no relevant documentation on the humidity records exist in the Andes, Vuille et al. (2008) could found a moderate rise in relative humidity between 1950 and 1995 in the Western Bolivia based on station data. One of the drawbacks in the study of ENSO impact on tropical glaciers in the past is that an advance (or a retreat) cannot be verified always due to the uncertainties in moraine dates and lack of satellite imagery or aerial photography.

6 Conclusions

Even though unexpected snowfall events sometimes cause the underestimation of ELA from SLA using satellite imagery, the selected images towards the end of dry season were excellent to calculate the snowline. In the outer tropics, the highest snowline during the dry season can be taken as the ELA of the year. From the results from this study, it is seen that the snowline of the Nevado Sajama, Nevado Cololo, and Nevado Huanacuni have been fluctuated between warm and cold phases of ENSO (combined with the warm and cold regimes of PDO, respectively) between 1984 and 2011. The significant snowline rise of the selected glaciers during 1990–1995 confirms the effect of El Niño, which persisted for a long period in phase with the warm PDO. In general, there was an overall increase in the snowline during this period, and this indicates that the climate condition in Bolivia is still warming. For a better understanding of this complex glacio-climatological process, other local climatic factors such as seasonal snowfall, wind speed, and sublimation characteristics of the glacier can be considered for future improvement.

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