VARIATIONS IN THE SNOWLINE ALTITUDE OF A MOUNTAIN GLACIER IN BOLIVIA AND ITS TELECONNECTION WITH PACIFIC DECADAL OSCILLATION AND EL NINO – SOUTHERN OSCILLATION

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ABSTRACT – This paper describes the variations in snowline altitude of Nevado Cololo, one of the snow patches situated in the Cordillera Apolobamba in Bolivia. Influence of Pacific Decadal Oscillation and El Nino – Southern Oscillation (ENSO) on this glaciated mountain was analyzed. LISS-III, CBERS-2, Landsat MSS, TM and ETM+ images taken during May-June-July were considered in this research. Precipitation and monthly mean temperature data from various gauging stations near the study sites in the form of gridded datasets were also analyzed. It is found that the glaciated area was also fluctuated with the occurrence of warm and cold phase of ENSO but its relative intensity is controlled by the variations in the warm and cold regimes of the Pacific Decadal Oscillation. Even though there was an oscillation in the retreat of Nevado Cololo with ENSO and PDO, there is a continuous retreating trend during the study period.

RESUMO - Este trabalho analisa as variações da altitude da linha de neve no Nevado Cololo, situado na Cordilheira Apolobamba (Bolívia), e as influências da Oscilação Decenal do Pacífico e do El Nino – Oscilação Sul (ENOS) nas variações acima citado. Para isso, utilizou-se imagens LISS-III, CBERS-2, Landsat MSS, TM e ETM+imagens dos meses de maio, junho e julho do período entre 1984 – 2011. Além disso, utilizou-se dados mensais de temperatura e precipitação disponibilizados pela Universidade de Delaware. Verificou-se que a linha de neve do Nevado Cololo varia com a ocorrência do ENOS, sendo que em períodos de El Niño observa-se a linha de neve em altitudes mais elevadas e em períodos de La Niña em altitudes menores, mas essa relação é predominante quando o ENSO e a Oscilação Decenal do Pacífico possuem mesma fase. Para finalizar, destaca-se a tendência contínua de retração do Nevado Cololo.

1 INTRODUCTION

Glaciers, particularly mountain glaciers and ice caps in the tropical region, are extremely sensitive to environmental fluctuations and are considered by many researchers as useful indicators of climate change. Retreat of mountain glaciers and ice caps were found to be linked directly with historical temperature records. Unfortunately, due to the absence of spatial and spectral data coverage, climate change in the tropical Andes in 20^{th} century is poorly documented. In a warming environment, when no change in precipitation occurs, smaller glaciers in the lower altitudes will disappear at faster rates. It is seen that between 1950 and 1994 an average warming of 0.09-0.15^{o}C decade^{-1} has been occurred and most of this warming occurred after 1970s (Vuille et al., 2003). El Niño - Southern Oscillation (ENSO) is a global scale ocean-atmosphere phenomenon, which causes climate variability on interannual time scales, with irregular fluctuations between its warm phase (El Niño), and cold phase (La Niña) with a periodicity of 2 to 7 years. ENSO is normally associated with sea surface temperature (SST) changes and hence can be monitored based on SST variations. Opposite rainfall and temperature anomalies were observed during the El Niño and La Niña events which show its impact on the tropical climate. Glacier recession in the tropical Andes is considered as due to large-scale climate effects rather than due to regional climate forcing (Vuille et al., 2003). Altitude of Glaciers in the central Andes ranges between 4000 m and 6500 m asl. Other than decreased precipitation, absorption of higher solar radiation also considered as a source of increased melting of glaciers. The Pacific Decadal Oscillation (PDO) is a climate index based on the North Pacific sea surface temperature (SST) variations with warm (positive index) and cold (negative index) regimes. Warm and cold regimes can persist for several decades. PDO can modulate the interannual relationship between the ENSO and global climate, and can cause interdecadal climate variability in the tropical Pacific (Mantua et al., 1997). Warm and cold regimes of PDO can persist for several decades. It is found that the decadal cycles of PDO have broken down since 1998. The focus of this research is on the combined influence of ENSO and PDO on glacier variations in the Bolivian Andes. Glaciers in the tropics are having two special features – they are subjected to higher levels of energy forcing due to their specific latitudinal and altitudinal location, and accumulation and ablation occurs simultaneously due to year-round precipitation (this equilibrium can be broken by climate imbalances). In the outer tropics, annual distribution of precipitation (particularly during December-February) influences the annual glacier melting. Glaciers in wet climate are more sensitive to temperature fluctuations than in a drier climate.

When the precipitation occurs in solid form (snowfall), glacier ablation and runoff are poorly correlated with the rate of precipitation (Francou et al., 1995). Glaciers in Bolivia belong to the outer tropics and there exists a specific precipitation season. It is believed that an increase in temperature without changes in precipitation can cause the disappearance of glaciers in the tropics (Rabatel et al., 2013). A large number of precipitation and temperature zones exist in the Andes and the glaciers in the Andes are influenced by the ocean-atmospheric circulation patterns. Precipitation variability is linked with atmospheric circulation on an interannual timescale. In glaciated mountain regions, if the seasonality in precipitation is absent, the population depends on the glacier melt water for their freshwater needs. In the case of a complete disappearance of glaciers in these regions, it will cause serious consequences on a massive population. ENSO events are considered as one of the factors, which cause precipitation anomalies in many places of the world. El Niño events are normally associated with below-normal precipitation and La Niña events with an above-normal seasonal precipitation, even though the effects of ENSO events differ between seasons. Since the rate of precipitation is linked with ENSO events, glacier mass balance changes also correlated with the occurrence of ENSO. However, it would not be ideal to consider short-lived ENSO events to understand fluctuations of mass balance on a decadal timescale. Hence, decadal events such as PDO are considered in this research. El Niño and La Niña events were known to affect the natural systems and economy in Bolivia for a long time.

Retreat of Andean glaciers in Bolivia, Ecuador, Chile and Peru since the Little Ice Age (LIA) is found to be discontinuous. Those lying in low altitudes undergone more rapid retreat compared to those in higher altitudes. Longwave radiation penetrating through the atmosphere provides the ablation energy in mountain environments. It is known that glaciers in different climatic conditions respond to climate fluctuations in different magnitudes. Since the glaciers in the Andes are situated in different climate conditions, different magnitudes of mass balances changes occurs. Direct measurement of mass balance is not always practical due to the absence of information. Instead, proxies of mass balance can be used. It is reported that glaciers in Bolivia retreated rapidly between 1975 and 1983, and again between 1997 and 2006 (Soruco, 2008). Periods of stability in the mass balance were observed during 1956-1975 and 1984-1996. Similar trends were observed in the case of Antizana 15 (Francou et al., 2000) and Cotopaxi (Veettil et al., 2014) in the Ecuadorian Andes during the occurrence of ENSO and PDO. Recent advances in remote sensing and photogrammetric techniques have been helped the scientific community to understand recent surface and mass balance changes, and evolution of tropical mountain glaciers, at least from the mid-20th century. Calculated SLA and ELA using remote sensing were utilized by many researchers (Arnaud et al., 2001; Rabatel et al., 2012) to calculate approximate mass balance changes and hence used as indicators of climate change in the outer tropics.

2 METHODOLOGY

In this research, one of the snow patches in Bolivia, Nevado Cololo (14^{o}50'S, 69^{o}06'W) in the Cordillera Apolobamba, is monitored and the snowline altitudes of three selected outlet glaciers were calculated (Figure 1). Bolivian land cover can be classified into three types based on altitudinal division. Lowlands (<800 m asl), Andean slopes (800-3200 m asl) and the Altiplano (>3200-6500 m asl). Annual precipitation varies from 300 mm to 3000 mm and annual mean temperature varies from zero to 30^{o}C. Higher precipitation season is from December to March. Three main sources of climate variability in Bolivia are 1) Pacific decadal oscillation (PDO), 2) El Niño-Southern Oscillation and 3) Antarctic Oscillation (AO). In this research, we considered the first two. Glaciers in Bolivia are situated in two mountain ranges – Cordillera Occidental along the western border with the Chile and the Cordilleras Apolobamba, Real, Tres Cruces and Nevado Santa Vera Cruz in the east. Southern Bolivia is devoid of glaciers at present due to limited precipitation. In Bolivia, glaciers in the Cordillera Occidental are limited to Navado Sajama and its neighboring ice-covered volcanoes in Chilean border. Bolivian glaciers belong to outer tropics, where lower temperature variability, high solar radiation influx throughout the year and seasonality of humidity and precipitation occurs. Cordillera Apolobamba, where the Nevado Cololo is situated, is separated from the Cordillera Occidental by the Altiplano. Monthly precipitation rates derived from a 30-year gridded datasets (1976-2008) at the Cololo region is given in Figure

2. Precipitation occurs by a mechanism called ´Amazonian Monsoon´ that causes about 80% of the annual precipitation. Majority of the glacier mass-balance changes occur during the austral summer and the ENSO events controls the interannual variability of mass balance. In this region, other than the variations in the Pacific SSTs, the mass balance changes of the snow patches are assumed to be depending on the Amazon circulation patterns as well. It can be argued that the rate of fluctuation of glacier in the two different cordilleras can differ from each other.

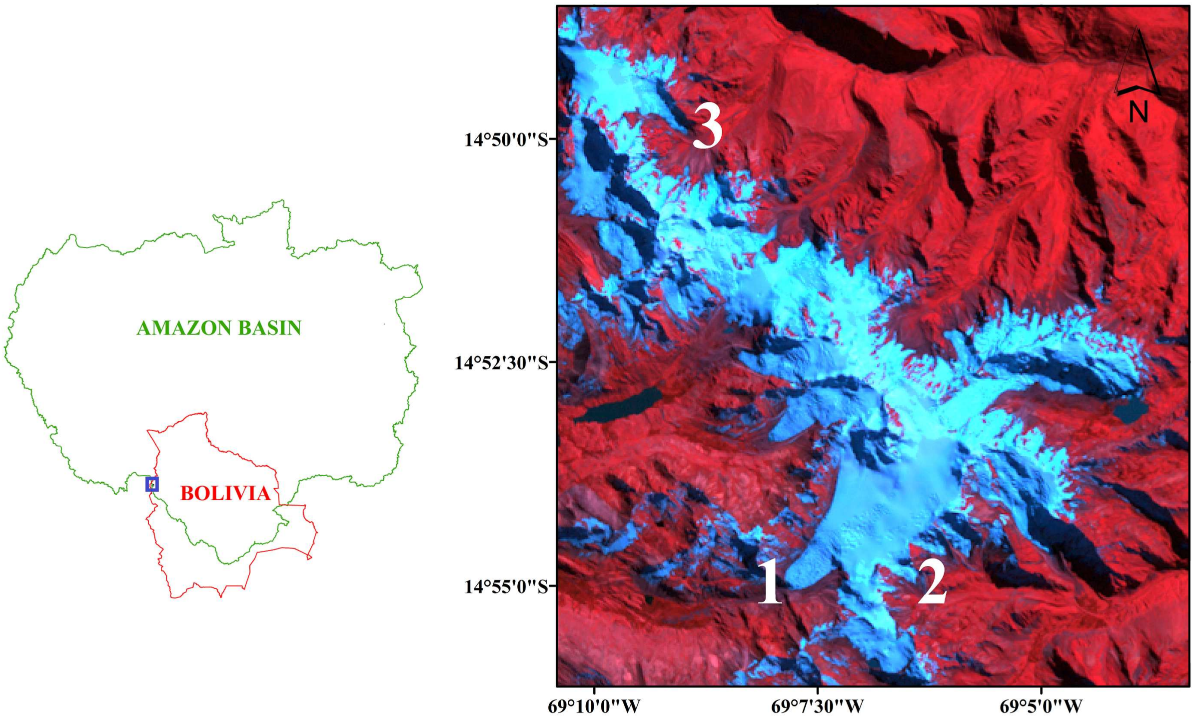

Figure 1 - Relative location of Nevado Cololo with the Amazon Basin and the selected outlet glaciers

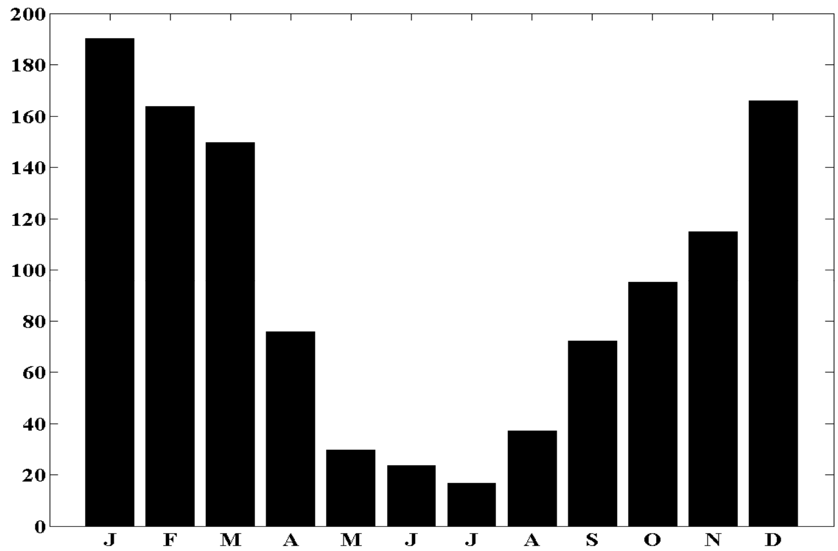

Figure 2 – Monthly mean precipitation in the Cololo region in mm

Two types of datasets used in this study. The first type is the remote sensing data, which consists of multispectral satellite images and digital elevation models. The second type of data is the meteorological data from various gauging stations near the study site and SST data. ENSO and PDO indices from Climate Prediction Centre (CPC) of the National Oceanic and Atmospheric Administration (NOAA) were also used in this study. Images from 1972 are available from Landsat series (MSS, TM, ETM+ and 8). Landsat TM, ETM+, CBERS-2 and LISS III images were used for this research. Landsat images are having a spatial resolution of 30 m in visible and infrared, 60 m in thermal and 15 m in panchromatic wavebands. Multispectral images of LISS III is having four spectral bands, three in VNIR and one in 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 taken during the end of summer months were considered in order to avoid the difficulty in delineation of glacier margin. Other than multispectral images, digital elevation models (DEMs) from ASTER global digital elevation models (GDEM) were also used in this research for calculating snowline altitudes. It is difficult to calculate the glacier area or SLA from satellite images during these highest or lowest precipitation seasons and hence all the images taken for this study were devoid of excessive snow cover as well. Co-registration of the images and DEMs were done and the images were radiometrically calibrated before further image processing algorithms. All the images were corrected with the solar zenith angle. Image processing steps were done using Erdas Imagine and ESRI ArcGIS 10.1 software packages. High resolution, gridded, Monthly precipitation and temperature (above 2 m from the ground level) station data with a horizontal resolution of 0.5^o lat-long during a period of 1979 to 2008 from the University of Delaware is used in this research. These data were derived from a large number of stations including Global Historical Climate Network (GHCN2) and archives of Legates & Willmott. Ocean Niño indices (ONI) from Niño 3.4 region were considered in this study. In this data, cold and warm episodes were defined when a threshold of +/- 5^oC is met for a minimum of five consecutive overlapping seasons. It is seen that the average sea surface temperature has been increased during 1975-2010. Monthly Pacific Decadal Oscillation (PDO), an index based on the variations in SST in the north Pacific, was downloaded from Joint Institute for the Study of the Atmosphere and Ocean (JISAO). The gridded datasets were processed using MATLAB.

Table 1 - Spectral coverage of the images used

Channel	**Spectral Range (µm)**				
	Landsat MSS	**Landsat TM**	**Landsat ETM+**	**CBERS-2**	**Resourcesat-1 LISS III**
BLUE		0.450-0.520	0.450-0.515	0.450-0.520	
GREEN	0.5-0.6	0.520-0.600	0.525-0.605	0.520-0.590	0.520-0.590
RED	0.6-0.7	0.630-0.690	0.630-0.690	0.630-0.690	0.620-0.680
NIR	0.7-0.8	0.760-0.900	0.775-0.900	0.770-0.890	0.770-0.860
SWIR1	0.8-1.1	1.550-1.750	1.550-1.750		1.550-1.700
TIR1		10.40-12.50	10.40-12.50		
SWIR2		2.080-2.350	2.090-2.350		
PAN			0.520-0.900	0.510-0.730	

3 RESULTS AND DISCUSSION

Image processing and meteorological data analysis were the two-step processes done in this research. Image processing steps were applied to the images for delineating glacier boundaries and calculating the snowline altitudes and hence to estimate mass balance changes. Proxy measurements of the mass balance changes can be done based on the changes in the end summer snowline (which is very close to equilibrium line altitude) or by repeated observation of the terminus changes. Highest SLA detected using satellite imagery during the dry austral winter could be used to estimate the equilibrium line altitude of the year (Rabatel et al., 2012). Usually, for the mid-latitude glaciers, snowline at the end of the hydrological year (end of summer) can be taken as ELA of the year. When calculated from proxy measurements, the glacier mass balance itself can be used as a climate proxy. Landsat TM3/TM5 and TM4/TM5 ratio images have been proved easier in distinguishing ‘clean’ glaciers from other land surface features by thresholding the ratio image. The method of thresholding ratio images is having a drawback of being sensitive to the influence from thin clouds. . Normalized Difference Snow Index (NDSI) images were also tried. It is known that NDSI images are excellent in the spectral discrimination of snow and other surface features like soil, rock, dust and water and proved to be suitable for snow cover mapping in rough topography. Even though NDSI can be used to discriminate the spectral characteristics of snow and ice, it is still inadequate to calculate SLA, particularly when the snout is covered with fresh snow. Rabatel et al (2012) adopted a methodology to calculate SLA using 5-4-2 false-color composite images that can be used to get a more accurate value of the ELA. TM4 and TM2 channels were applied with threshold values of 60 to

135 and 80 to 160 respectively before creating the 5-4-2 composite image. The resulting images can be used to map the SLA successfully. The result of the SLA calculations at Nevado Cololo is summarized in Figure 3. It is interesting to note that the response of SLAs with PDO is higher in this case than compared to those in Ecuador (Veettil et al., 2014). This can be possibly due to either 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 (Veettil et al., 2014) were interfered due to the absence of a fixed precipitation season. We analyzed the anomalies in precipitation and temperature in the Cordillera Apolobamba in a similar way as described in Veettil et al (2014) using the gridded datasets from University of Delaware. Two sources of climate variability in the South America were also considered – ENSO and PDO. The observed ENSO and PDO variations are given in Figure 4.

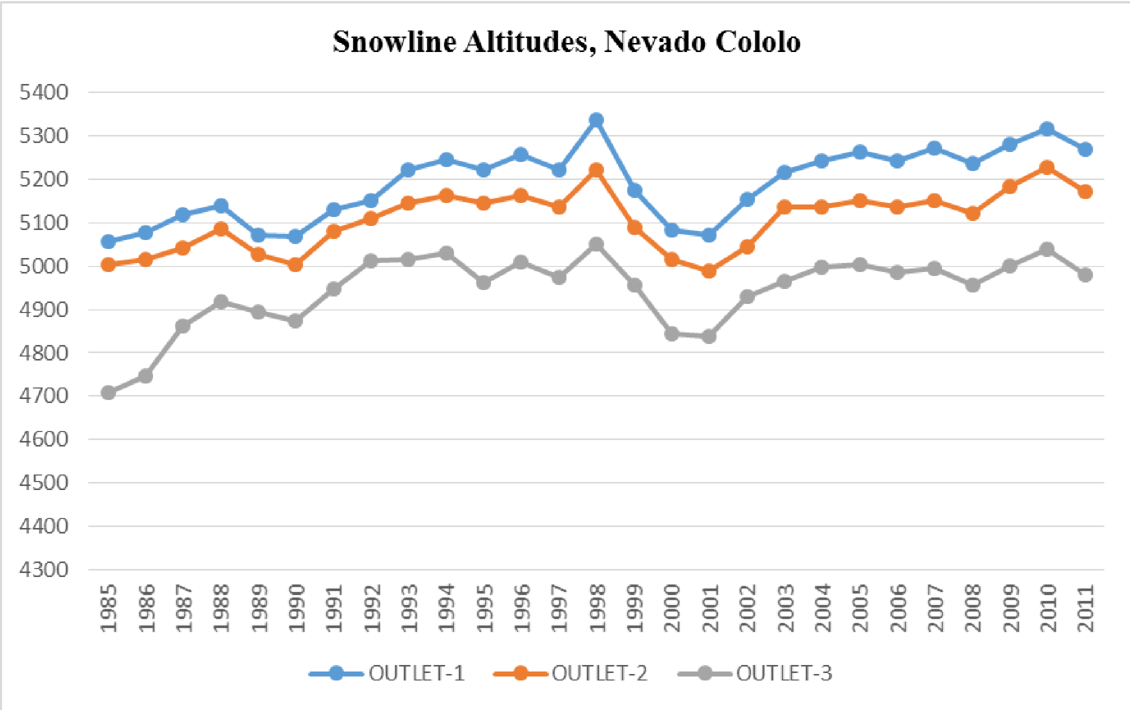

Figure 3 – Snowline Altitudes from 1985 to 2011

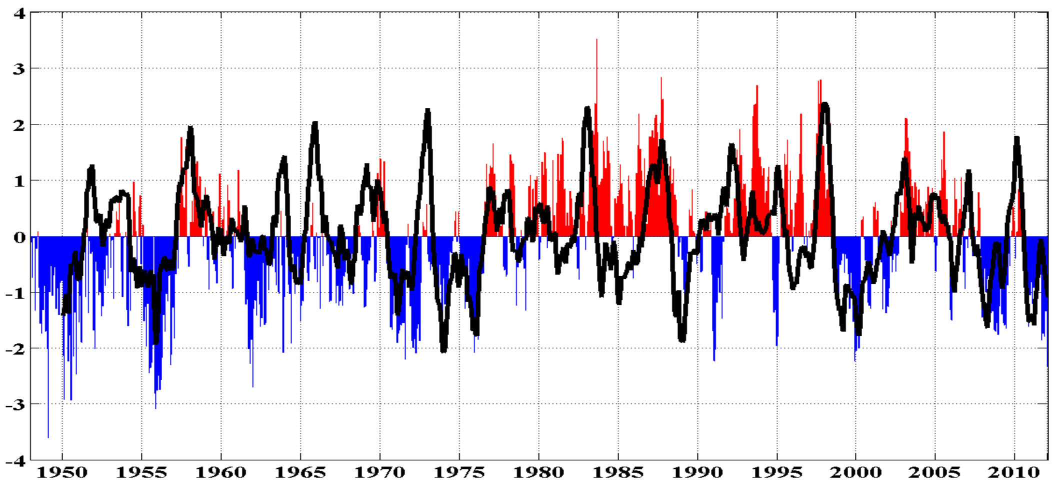

Figure 4 – ENSO and PDO (red and blue) indices from 1948 to 2014

Glaciers in different climatic situations respond to similar climatic variations differently. In a warming climate, higher wintertime temperature can accelerate glacier ablation. Main moisture source for precipitation in the Altiplano is transported from the eastern lowlands of the Andes, which is highly dependent on the tropical SSTA variations (Vuille et al., 2000). In this study, it is assumed that the Cordillera Oriental is more influenced by Atlantic and Amazon circulation compared with the Cordillera Occidental, which is more influenced by the Pacific circulation. El Niño events induces precipitation deficits in the outer tropics which in turn promotes glacier melting whereas in the inner tropics, temperature increase associated with ENSO events causes augmented melt rates. Moreover, rate of liquid precipitation rates are higher in the inner tropics whereas solid precipitation is almost absent in this region, which is common in the outer tropics (Favier et al., 2004). A common response to climate, decrease in glacier mass since 1975, is found among the glaciers in the Cordillera Real (Soruco, 2008). Other than altitudinal variations, the rate of decrease in the glacier mass is highly dependent on other 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). Two main characteristics distinguish the PDO from ENSO. Firstly, typical PDO events have shown remarkable persistence relative to that attributed to ENSO events - in this century, major PDO eras have persisted for 20 to 30 years. Secondly, the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signatures exist in the tropics - the opposite is true for ENSO. It is seen that there is an imbalance in the frequency of occurrences of PDO after 1998-1999. The warm phases observed to be dominating recently until 2006.

4 CONCLUSIONS

Summer months (December – March) accounts for majority of the annual mass variability in Bolivia (Soruco et al., 2009). Snowfall events often cause underestimation of ELA from SLA using satellite imagery. The selected images were towards the end of summer months and are excellent to calculate the SLA. This SLA value can be taken as a measure for ELA during this season in the outer tropics. From the results obtained above, it is clear that the glaciated area and snowline altitudes of the Nevado Cololo have been fluctuated between warm and cold phases of ENSO (combined with the warm and cold regimes of PDO) between 1984 and 2011. Multitemporal satellite images can be used as a powerful tool in the glacier research, particularly by calculating the SLA and glacier area for understanding climate imbalances in the tropics. In general, there was an overall increase in the snow line altitude during this period and this indicates that the climate condition in Bolivia is still warming. The suitability of SLA in analyzing mass balance changes with climate variations (Arnaud et al., 2001; Rabatel et al., 2012) has been proved in this study. The significant increase in the SLA and drop in the area occupied by the glacier during 1990-1995 strongly confirm the effect of El Niño, which persisted for a long period. The chances of errors using ASTER derived DEMs are the elevation errors and altitudinal bias. Other local climatic factors must be taken in to account before reaching a conclusion. It would be also helpful to consider variations in the southern tropical Atlantic SST variations in order to calculate teleconnection, if any exists, between the tropical atmospheric circulation anomalies and mass balance changes of glaciers in the outer tropics.

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