The use of snowline altitude of mountain glaciers as indicators of climate change in the tropical Andes from remote sensing data: a case study on Nevado Sajama, Bolivia

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Abstract. This paper describes the application of remote sensing for the estimation of the snowline equilibrium altitudes of mountain glaciers in the outer tropics and the use of snowline altitudes as a valuable approximation of the equilibrium line altitude of the year and hence to get the most proximal estimation of annual mass balance changes. In this case study, we used the images from Landsat series – MSS, TM, ETM+ and Landsat 8 - images of the Nevado Sajama in the Western Cordillera in Bolivia. Snowline altitude of a selected outlet glacier of the study site for each year during the dry season was calculated and the maximum snowline calculated during the dry season can be taken as the equilibrium line altitude of the year. Anomalies in precipitation and air temperature were calculated and compared with the observed differences in the calculated annual snowline changes. We also considered three ocean-atmospheric oscillations in the Pacific – ENSO, PDO and AAO. It is found that the snowline altitude of this mountain glacier have been fluctuated with the cold and warm regimes of ENSO and PDO. It is hypothesized that the retreat of this mountain glacier in the Western Cordillera is not as rapid as the Eastern Cordillera in the outer tropics, probably due to the cold regimes of PDO and high altitude of the Nevado Sajama retards the rapid ablation in this region.

Keywords: Mass balance, Landsat, Equilibrium line, Cordillera Occidental, Outer tropics.

1. Introduction

Mountain glaciers are found to be retreating faster than ever during the last few decades. Tropical glaciers were found to be highly sensitive to climate variations and show a rapid response to such variations (Arnaud et al., 2001). In the context of global warming, glaciers in the tropics also contribute significantly to the sea level rise (Valentina, 2008). A significant amount of tropical glaciers are situated in the Andes and various models suggest an increase in temperature at high altitudes in the tropical Andes (Vuille et al., 2008). Andean glaciers in Ecuador, Peru and Bolivia have been undergoing retreat since the Little Ice Age (Kaser, 1999; Rivera et al., 2005). Ablation characteristics of topical glaciers are sensitive to various factors such as albedo, air temperature, vapour pressure, humidity, sublimation and precipitation (Vuille et al., 2008; Veettil et al., 2014).

Aerial photographs and satellite images are the only way to study many glaciers due to the difficulty in field survey or inaccessibility due to geopolitical reasons. Due to the emergence of various sensors from the mid 20th century, it is now possible to calculate the glacier changes from the late 1960s to the present. The spatial and spectral resolutions of multispectral images have been improved from time to time. Various glacier parameters such as snowline altitude, area, surface elevation and terminus can be calculated from these images (Aniya et al., 2000; Arnaud et al., 2001; Bamber and Rivera, 2007; Rabatel et al., 2012;

Veettil et al., 2013). The glacier parameter considered in this research is the snowline altitude (SLA) of a glaciated mountain in the outer tropics in Bolivia.

Three ocean-atmosphere phenomenon influences the climate in the outer tropics - El Niño – Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and Antarctic Oscillation (AAO) (Seiler et al., 2013). ENSO is an ocean-atmosphere phenomenon which originates in the tropical Pacific and causes climate variability on interannual time scales between warm (El Niño) and cold (La Niña) phases (Garreaud et al., 2009). El Niños in the outer tropics are associated with draught and higher glacier melt rates. PDO is a climate index based on the north Pacific SST variations and its principal difference with ENSO is that the warm and cold regimes of PDO can persists for several decades (Mantua et al., 1997). PDO can modulate the correlation between ENSO and tropical climate near the Pacific coast. AAO is the southern counterpart of Arctic Oscillation (AO) in the northern hemisphere and is found to be occurring in opposite phase with ENSO. AAO is the dominant pattern of non-seasonal tropospheric circulation variations to the south of 20ºS and is also referred to as Southern Annular Mode (SAM). In this paper, we considered all the above mentioned three oscillations.

2. Study site

Bolivia is considered as a tropical country with its main altitudinal divisions consists of lowlands (<800 m ASL), Andean slopes (800-3200 m ASL) and the highlands or the Altiplano (>3200-6500 m ASL). We considered Nevado Sajama (18º06'S, 68º50'W) in the Bolivian Altiplano in the outer tropics (Figure 1) as representative of tropical glacier for understanding the suitability of SLA as a proxy to estimate the equilibrium line altitude (ELA) of the year which itself is a proxy of mass balance of the year. Nevado Sajama is having an altitude of 6542 m asl and is the only glacier situated in the Cordillera Occidental in Bolivia. Sajama volcano is the southernmost tropical glacier and is the highest point of Bolivia. It is situated about 100km to east of the Peruvian Pacific coast on the Altiplano and hence is well suited to study the influence of ocean-atmospheric oscillations in the Pacific on the tropical glaciers (Arnaud et al., 2001).

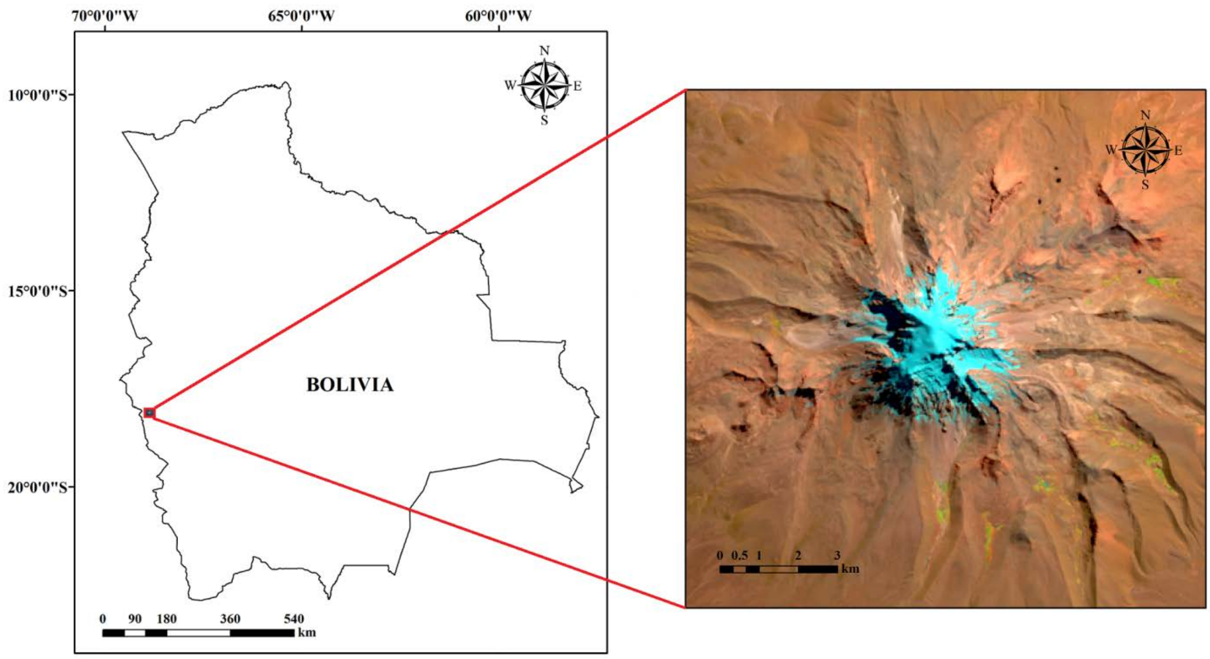

Figure 1. Location of Sajama Ice-covered volcano and the outlet used to calculate SLA

Climate in Bolivia varies from tropical to cold desert climate depending on the altitude (Seiler et al. 2013).The climate near the Sajama is semiarid and annual precipitation is about 350 mm per year. Majority of precipitation is during December to March (Figure 2). The maximum ablation and accumulation in this region is during the rainy season (from October to March) even though the mid-latitude glacier ablation and accumulation seasons are individual (Ribstein et al., 1995). Precipitation and its interanual variability is linked to tropical SST anomalies and atmospheric circulations (Arnaud et al. 2001; Vuille 1999). Austral summer (DJF) is characterized by low pressure system which enhances the easterly trade winds to transport moisture from the Atlantic (northern tropics) to the continent. 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 2000). Seiler et al (2013) calculated that the Bolivian climate is warming at the rate of 0.1ºC in every decade and follow the PDO patterns based on meteorological observations,. During the warm phase (El Niño) precipitation is lesser than normal which causes accelerated glacier ablation due to the reduced surface albedo (Arnaud et al., 2001). On the other hand, during cold phase (La Niña), surface albedo is higher due to higher precipitation rates which favor accumulation.

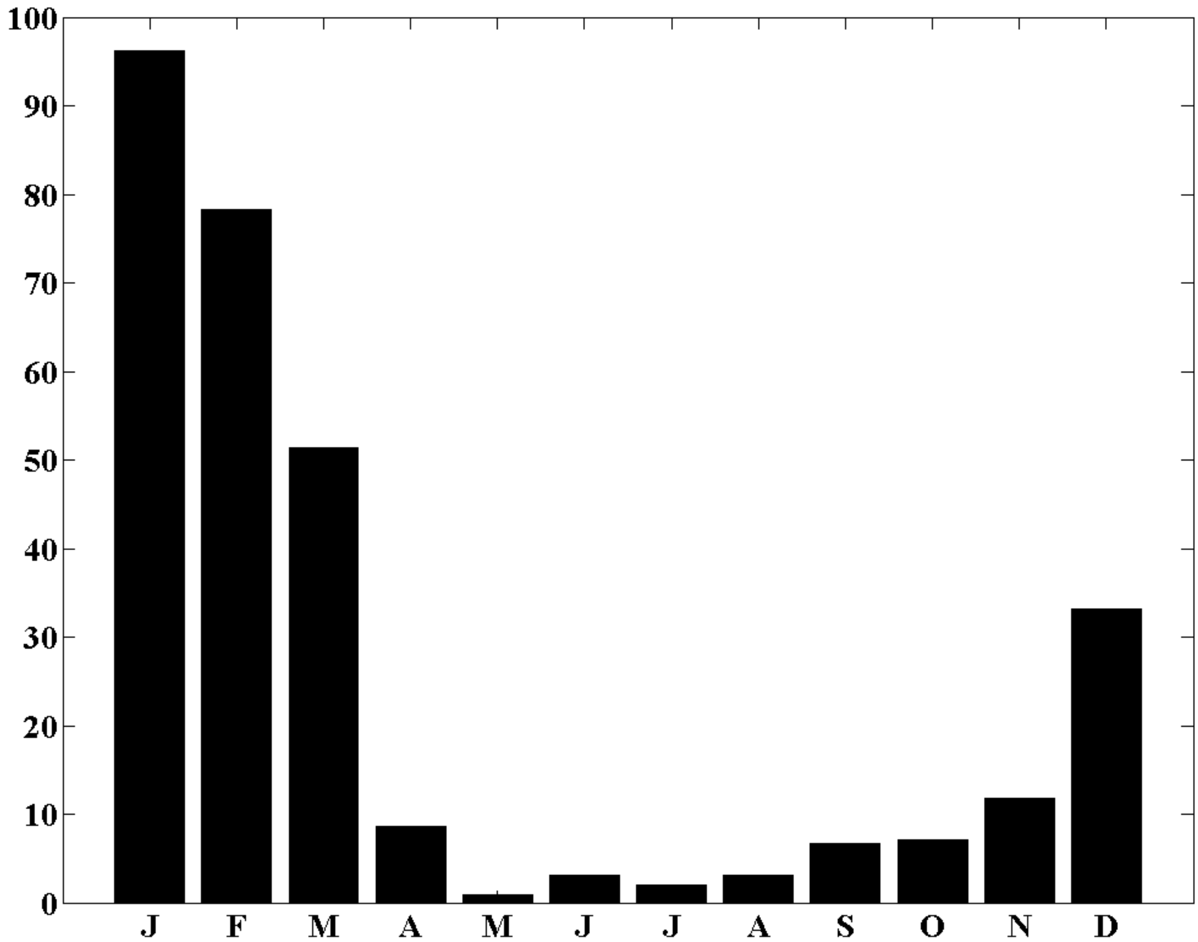

Figure 2. Monthly mean precipitation near Nevado Sajama

3. Materials and Methods

We used images from Landsat series here acquired from 1984 to 2014 (TM, ETM+ and Landsat 8). These images are having a spatial resolution of 30 m in visible and infrared, delivered as 30 m in thermal (TM, ETM+ and Landsat 8 are acquired at 120 m, 60 m and 100 m respectively in the thermal channel) and 15 m in panchromatic wavebands (ETM+ and Landsat 8). Spectral coverage of the images used for this research is given in table 1 given below. Images taken during the period of May to August (dry season) were used because it is free from clouds, snow cover and difficulty in delineation of ice margin due to excessive ablation. Digital elevation models (DEM) from ASTETR global DEM (GDEM) is also used to calculate the annual SLA.

Table 1. Spectral coverage of the images used

Channel	**Spectral Range (μm)**		
	Landsat TM	**Landsat ETM+**	**Landsat 8**
Coastal Aerosol			0.430-0.450
Blue	0.450-0.520	0.450-0.520	0.450-0.510
Green	0.520-0.600	0.520-0.600	0.530-0.590
Red	0.630-0.690	0.630-0.690	0.640-0.670
Near IR	0.760-0.900	0.770-0.900	0.850-0.880
Mid IR1	1.550-1.750	1.550-1.750	1.570-1.680
Mid IR2	2.080-2.350	2.090-2.350	2.110-2.290
Cirrus			1.360-1.380
Thermal IR	10.40-12.50	10.40-12.50	10.60-11.19 11.50-12.51
Panchromatic		0.520-0.900	0.500-0.680

Monthly precipitation and temperature data, which are having a horizontal resolution of 0.5^{o} lat-long, during 1979-2011 downloaded from the University of Delaware were also used in this research. These data are derived from a large number of climate stations around the study site. Ocean Nino Index (ONI) is downloaded from National Oceanic and Atmospheric Administration (NOAA) and the PDO and AAO indices from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO). Images were processed using Erdas Imagine software and the meteorological data were analyzed using MATLAB.

Radiometric calibration based on Markham and Berker (1986) was applied to all the images before calculating the SLAs. We calculated the snowline altitude of the Nevado Sajama during the dry season of each year from 1984 to 2014. The highest value of the calculated snowline towards the end of dry season gives an approximate value of the equilibrium line altitude of the year (Rabatel et al., 2012). Mid-Infrared (TM5, 1.55 - 1.75 μm), Near Infrared (TM4, 0.76 - 0.90 μm) and Green (TM2, 0.52 - 0.60 μm) channels in TM is capable of differentiating snow and ice from other land surface features such as rock, soil and water. However, these channels cannot be used directly to differentiate between snow and ice which is important to estimate the snowline. Moreover, presence of think cloud in the images makes it further difficult to discriminate the snowline. We applied a methodology based on Rabatel (2012) to calculate SLA using 5-4-2 false-colour composite image. TM4 and TM2 channels were applied with threshold values of 60 1 to 135 and 80 to 160 respectively before creating the 5-4-2 composite image. Then using the DEM, calculate the SLA based on the snowline obtained from the 5-4-2 composite image. The resulting images can be used to map the SLA successfully. Coregistration of the images and DEM is necessary to get an accurate and comparable value of the SLA. Due to the rough topography and cast shadow, we selected an outlet glacier in the north-east corner only. Figure 3 shows the selected outlet glacier of Nevado Sajama before and after applying the thresholds. Arnaud et al. (2001) showed that the snowline altitude of Nevado Sajama has fluctuated during the El Niño event during 1997-1998 based on a study using remote sensing and aerial photography.

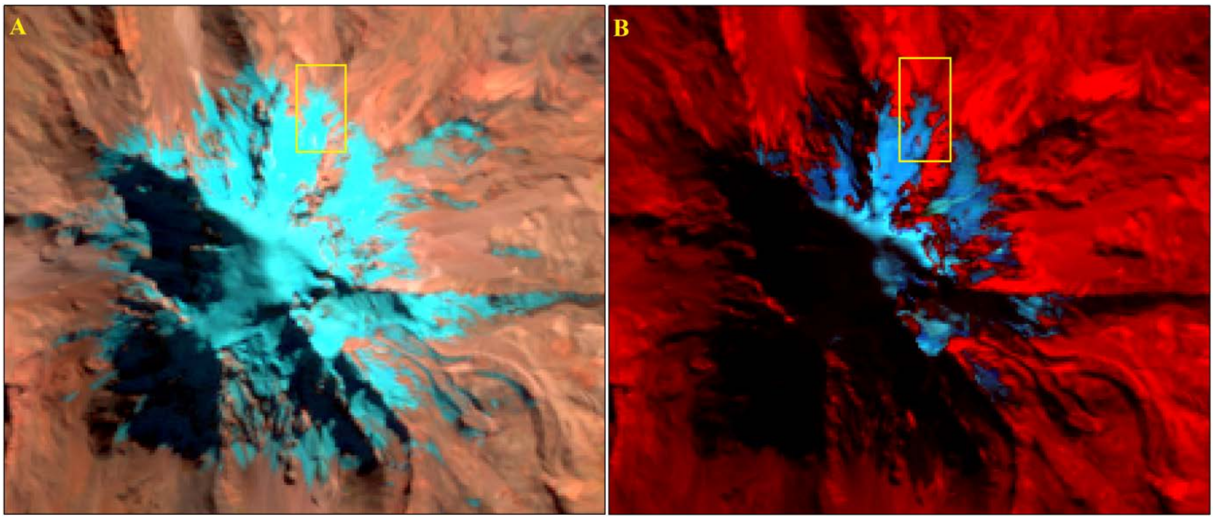

Figure 3. Image subset (5-4-2 composite) before (A) and after (B) applying threshold values

4. Results

The calculated SLA of Nevado Sajama from 1984 to 2014 is summarized in Figure 4. We compared our results during 1984 – 1999 with those obtained by Arnaud et al (2001) as well and it is seen that both the results were comparable. It should be noted that in Arnaud et al (2001), the boundary between snow cover and bare soil was taken as ‘snowline’. It is seen that the highest value of SLA was found during the strong El Niño during 1997-1998. It is also noted that when the warm phase of ENSO coincide with the warm regime of PDO, strong ablation was occurred and the snowline was moved back to a higher altitude. We could not find any direct influence of AAO on the SLA variations from the obtained results. Figure 5 shows the three indices considered in this research. Unlike continuous glacier retreat as reported in the case of Nevado Illimani in the Eastern Cordillera, the study site is showing non-continuous variations in snowline, probably due to the influence of cold phases of ENSO and PDO. However, a weaker monthly precipitation rate is observed at Sajama compared with Illimani probably due to the influence of Amazonian circulation at the latter location.

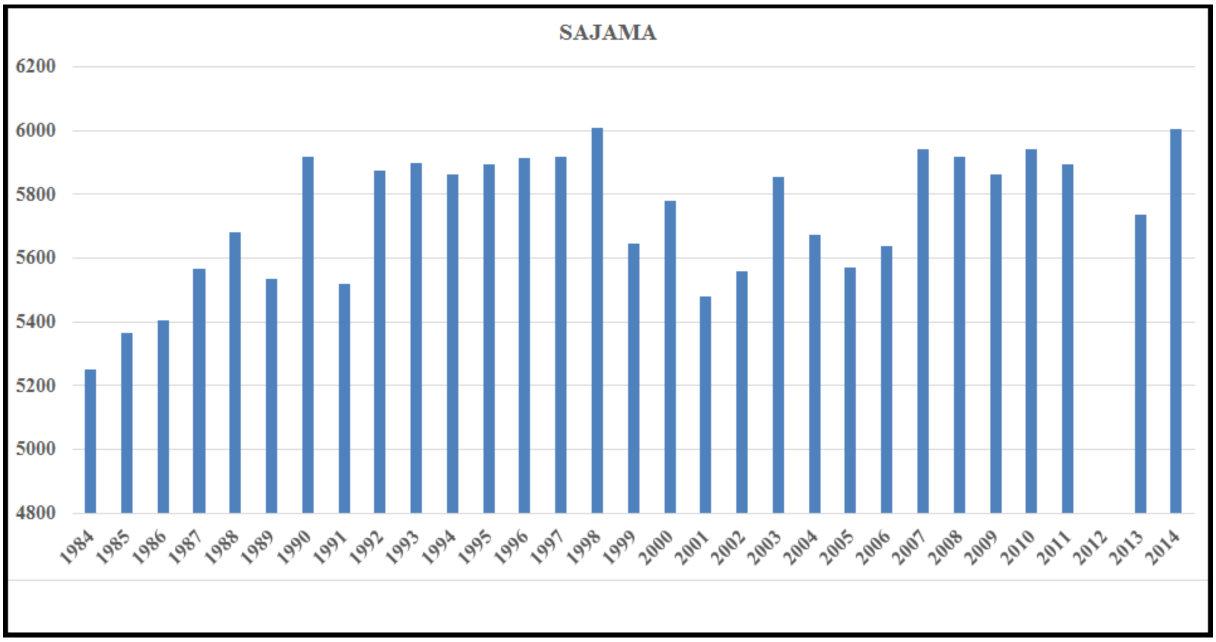

Figure 4. Variations in the SLA (in meters) of the selected outlet glacier of Nevado Sajama

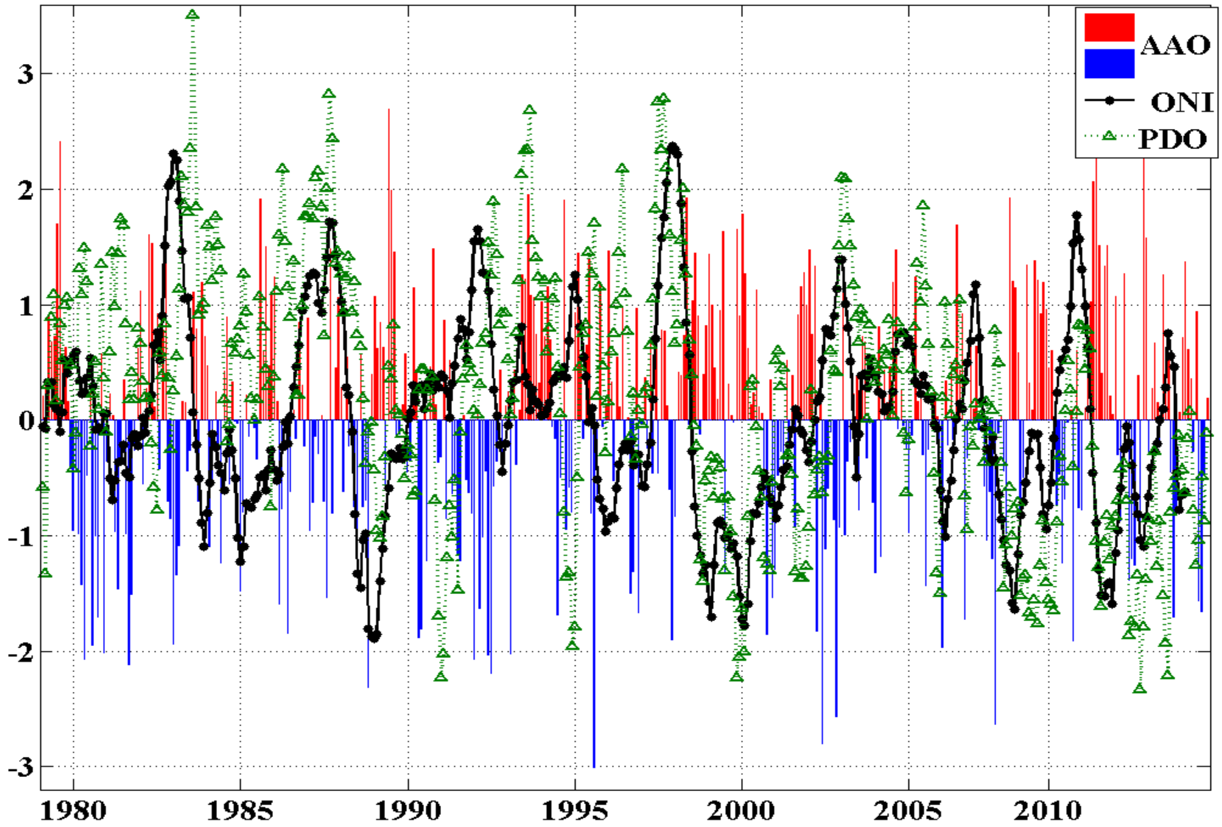

Figure 5: ENSO, PDO and AAO indices during 1979-2014

5. Conclusions

This research has been proved that snowline altitude can be used as a measure of mass balance fluctuations in the outer tropics and satellite images can be used for this purpose. From this research, it is seen that the snowline altitude of Nevado Sajama had fluctuated with the cold and warm phases of ENSO during 1984-2014. Higher retreat was found during the strong El Niño event during 1997-1998. It is also noted that during 1998-1999, the rate of retreat is less, due to the prevailed strong La Niña conditions. A rapid ablation occurs when the warm phase of ENSO (El Niño) coincides with the warm regime of PDO. Higher wintertime temperature can accelerate rapid glacier ablation. If the glacier location is above 0^{o}C isotherm, the glacier would be more sensitive to precipitation variability and less sensitive to temperature variability (Kaser and Osmaston, 2007). In a warming environment, when no change in precipitation occurs, smaller glaciers in the lower altitudes will disappear at faster rates (Chevallier et al., 2011) due to the lowering of accumulation/ ablation ratio. Glaciers in Bolivia have retreated rapidly between 1975 and 1983 and again between 1997 and 2006 (Soruco, 2008). In general, there was an overall increase in the snow line altitude during this period and this indicates that a warming condition in Bolivian climate exists.

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