

The 2015/16 El Niño-related glacier changes in the tropical Andes

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Abstract Significant changes in the area and snowline altitude of two glacierized mountains – Nevado Champara (Cordillera Blanca, Peru) and Cerro Tilata (Cordillera Real, Bolivia) – in the tropical Andes, before and after the recent El Niño in 2015/16 period, have been analysed using Sentinel 2A and Landsat data. It is seen that the recent El Niño has been accompanied by higher fluctuation in glacier coverage on Nevado Champara and the loss of glacier coverage on Cerro Tilata was very high during the past 16 years. Rise in snowline altitude of selected glaciers was very high after the 2015/16 El Niño. Increase in the area covered by snow and ice during the La Niña periods were not enough to cover the ice loss occurred during the previous El Niño events and the strongest El Niño in 2015/16 was followed by a significant loss of ice-covered areas in the tropical Andes. Freshwater resources in this region will be affected in the near future if the current trends in glacier decline continue. Adaptation strategies need to be implemented to reduce the impacts of the continuing loss of glacierized on regional communities in the tropical Andean region.

Keywords ENSO, tropical Andes, glacier loss, snowline altitude, Sentinel 2A

1 Introduction

It has been observed that the tropical Andean glaciers in South America are undergoing a fast retreat since the Little Ice Age (Francou et al., 2003) and an unprecedented shrinkage occurred since the early 21st century in parallel with the glacial changes in the rest of the world (Rabatel

et al., 2013; Zemp et al., 2015). It has been projected that high altitude mountains, including those of the tropical Andes, will experience increased warming towards the end of the 21st century, compared to low elevation coastal areas (Bradley et al., 2006; Mountain Research Initiative EDW Working Group, 2015). The importance of monitoring tropical Andean glaciers, particularly in Bolivia and Peru, is clear from the recent research papers on the extent of damage due to glacier loss in this region on water resources during the dry season (e.g., Baraer et al., 2012; Soruco et al., 2015), ecosystem (e.g., Buytaert et al., 2006; Anderson et al., 2011; Dangles et al., 2017; Polk et al., 2017), avalanches and glacial lakes outburst floods (e.g., Carey, 2005; Chevallier et al., 2011; Cook et al., 2016), agricultural economy and industry (e.g., Vergara et al., 2007; Mark et al., 2010) and human health (e.g., Epstein et al., 1998; Poveda et al., 2001). Recent reviews (Vuille et al., 2008, 2018; Rabatel et al., 2013; Veettil et al., 2017a) have also showed a clear picture of diminishing glacier coverage in the tropical Andes and its possible impacts on regional communities.

It has been demonstrated in recently published research and review papers that other than global warming, annual and decadal variability in sea surface temperatures (SSTs) in the Pacific also influence the rapid melting of glaciers in the tropical Andes by means of ocean-atmosphere climate interactions such as El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) (Arnaud et al., 2001; Francou et al., 2004; Veettil et al., 2014, 2016a, b, 2017a; Maussion et al., 2015). This influence is due to the alteration in the interannual climate variability of the South American continent by ENSO (Garreaud et al., 2009). The strongest El Niño of the second half of the 20th century in 1997/98 had remarkable influence on tropical Andean glaciers (Arnaud et al., 2001; Francou et al., 2003) due to the rise in the air temperature and reduction in precipitation during this period. Opposite conditions prevail during La

Niña events— i.e., reduction in the air temperature and increased precipitation (Arnaud et al., 2001; Garreaud et al., 2009). This distinct change in 1997/1998 is also thought to have been related to alpine lake changes, which is driven by large-scale atmospheric circulation changes (Zhang et al., 2017). Furthermore, it has been observed that the influence of ENSO on glacier melting was stronger when El Niño occurs during the warm phase of PDO or La Niña occurs during the cold phase of PDO (Veettil et al., 2017b). Vuille et al. (2018) observed that the impacts of ENSO on tropical Andean glaciers are relatively immediate whereas some delay (up to an 8-year lag) were observed for occurring PDO-related glacier changes in this region.

In a recent study, Thompson et al. (2017) tried to understand the influence of the 2015/16 El Niño, which is also considered a strong one, on tropical glaciers in Peru by analysing $\delta^{18}\text{O}$ isotopes from ice core samples. This study observed an enrichment of $\delta^{18}\text{O}$ isotopes during 2015/16 El Niño, which indicated a lower accumulation rate compared to the previous 15 years. In the present study, we estimated the changes in two glacier variables – snowline altitude and area – of two glaciers in the tropical Andes before and after the 2015/16 El Niño using satellite images. Furthermore, we tried to observe if any remarkable changes have occurred to selected glaciers in the tropical Andes.

2 Study site

The tropical Andes of Peru and Bolivia belong to the outer

tropics (Fig. 1(a)), where seasonal precipitation occurs (Favier et al., 2004) and this region hosts more than 90% of all tropical glaciers in the world (Randolph Glacier Inventory – Tad Pfeffer et al., 2014). In order to understand the changes in glacier variables in the outer tropics, two glaciers (Fig. 1(b)) were selected – Nevado Champara ($8^{\circ}41'S-77^{\circ}46'W$; maximum elevation 5735 m a.s.l.) situated in the northern end of Cordillera Blanca (Peru) and Cerro Tilata ($16^{\circ}15'S-68^{\circ}05'W$; maximum elevation 5336 m a.s.l.) in the southwest of Telapa Lake in the Cordillera Real (east of Bolivia).

The selected set of glaciers can be used to understand this difference in ENSO influence on glaciers in the outer tropics. There are some differences in the size and maximum elevation of glaciers selected for this study and which need explanation. Normally, smaller glaciers with low elevation are more influenced by rise in the air temperature (Ramírez et al., 2001). In this case, Nevado Champara has higher elevation and surface area compared with Cerro Tilata and, hence, a rise in the air temperature associated with El Niño might have higher influence on Cerro Tilata, if the distance from the Pacific Coast does not influence effects of ENSO in glaciers in the outer tropics.

It has been observed that the glacierized areas near the Pacific Coast have experienced a stronger influence of ENSO (Arnaud et al., 2001) compared to those glaciers in the eastern cordilleras in Peru and Bolivia (Veettil et al., 2017c), which is also needs to be tested here during the 2015/16 El Niño. The 2015/16 El Niño was classified as a very strong one (after the 1997/98 El Niño) and gives an opportunity to verify if it has a relevant effect on glaciers in the tropical Andes. Some studies (e.g., Veettil et al., 2017a)

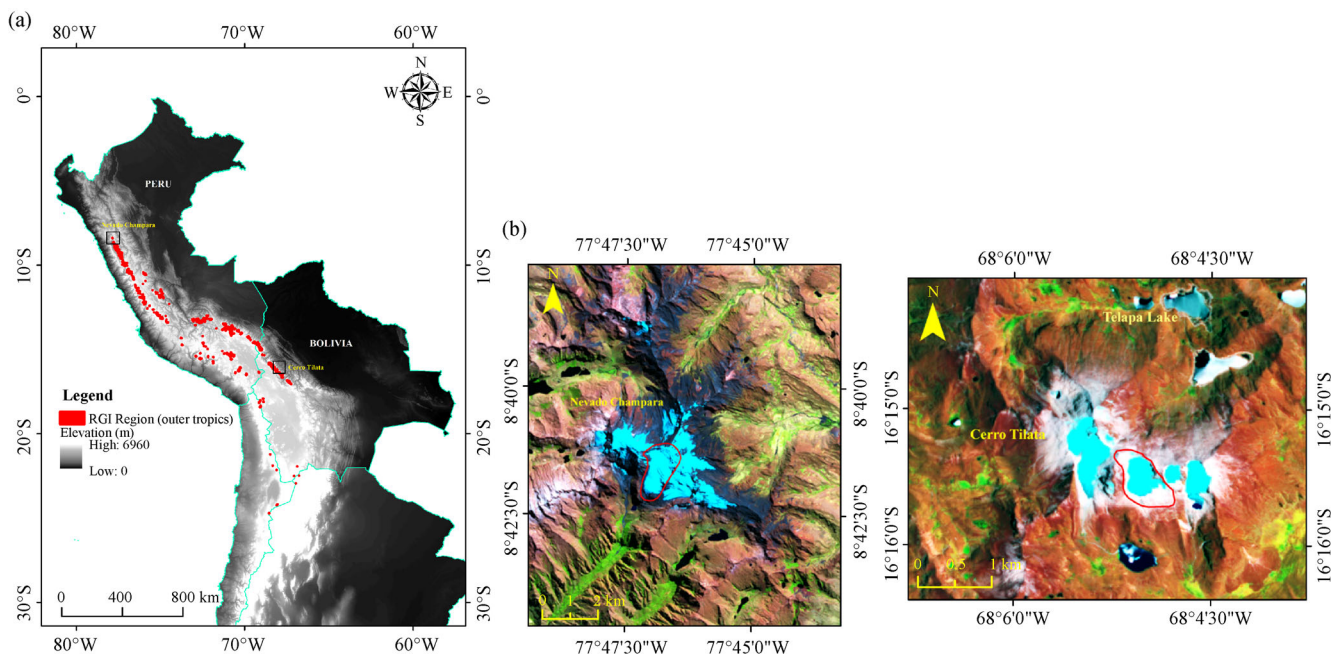


Fig. 1 (a) Glacierized areas of the outer tropics; (b) glacierized peaks considered for this study (glaciers shown within the red polygon were considered to estimate snowline altitudes).

hypothesised that snowline altitude and area of glaciers in the western cordilleras of Peru and Bolivia fluctuated during the phase changes of ENSO whereas relatively continuous shrinkage of glaciers occurred in the eastern mountain ranges. El Niño and La Niña events occurred after May 2001 with various strengths are summarized in Table 1. The period 2000–2002 was an ENSO-neutral phase, where no sufficient anomalies in the Pacific SSTs have been reported that indicate El Niño or La Niña.

3 Data and methods

Satellite images taken during the austral winter in the outer tropics can be used successfully to estimate glacier variables such as snowline altitude (Rabatel et al., 2012), area, and terminus altitude (Veettil and Kamp, 2017; Veettil et al., 2017c). Here we estimated area and snowline altitude after the ENSO-neutral conditions in 2001 to the recent La Niña condition in 2017 using Landsat image series (Thematic Mapper – TM, Enhanced Thematic Mapper Plus – ETM+, and Operational Land Imager – OLI), recent Sentinel 2A (Multispectral Instrument – MSI) data and digital elevation models (ASTER GDEM). Landsat images and DEMs have a spatial resolution of 30 m and MSI wavelengths used for this study have 10 m and 20 m resolution (depending on the wavelength range). Only the satellite data acquired during the austral winter were used and the images were verified visually for the presence of fresh snow (images with recent snow were not used). All these datasets were obtained from the United States Geological Survey (<https://earthexplorer.usgs.gov/>). In order to compare glacier changes during the occurrence of ENSO, Ocean Niño Index (ONI) from NOAA-Climate Prediction Centre (<http://origin.cpc.ncep.noaa.gov/>) was used.

Snowline altitudes were estimated using the method applied by Rabatel et al. (2012) and later followed by Veettil et al. (2016a, b, 2017b) in the tropical Andes. Here, the variation in maximum snowline altitude calculated at the end of dry season (austral winter: May–October) was taken as the approximate for changes in the equilibrium

line altitude. A TM 5-4-2 false-colour composite image (6-5-3 for OLI images) was created and then applied a suitable threshold value to near-infrared (TM 4) and green (TM 2) channels to separate snow and ice. The threshold digital number value applied to TM4 (near infrared) varies between 60 and 135 and that for TM2 (green) between 80 and 160. The resulting images show the boundary between snow and ice. Once the snowline has been delineated, the snowline altitude has been estimated with the help of DEM. Followed by Rabatel et al. (2012), only those glaciers with slope $> 20^\circ$ were considered for reducing errors while calculating their snowline altitudes, which helps to minimize the vertical errors due to steep terrain.

Glacier area was estimated using the normalized difference snow index (NDSI = $[\text{Visible} - \text{SWIR}] / [\text{Visible} + \text{SWIR}]$) after applying a suitable threshold (between 0.45 and 0.55). This method is widely used in the tropical Andes for delineating glacier boundary (e.g., Silverio and Jaquet, 2005; Veettil et al., 2016a). ± 1 pixel error has been assumed to have associated with the glacier area calculations (Frey et al., 2012). For Landsat images with 30 m spatial resolution, the ± 1 pixel error can be defined as:

$$A_{\text{err}} = \pm 9000 \times n / A_{\text{ga}}, \quad (1)$$

where, A_{err} is the ± 1 pixel error associated with glacier area, A_{ga} is the glacier area estimated from the Landsat data and n is the number of pixels defining the perimeter of a glacier polygon.

4 Results

4.1 Snowline changes between 2002 and 2017

Snowline changes during the end of dry season (austral winter) for the period 2002–2017 indicated a teleconnection with moderate-to-strong ENSO phase changes (Fig. 2). The rise in snowline altitude was very high after the 2015/16 El Niño. Both the La Niña events in 2007/08 and 2010/11 were associated with a slight fall in the snowline altitudes of both the glaciers. It has been

Table 1 Occurrences of El Niño and La Niña since for the period between May 2001 and October 2017 based on the running 3-month mean SST anomaly for the Niño 3.4 region (5°N – 5°S , 120°W – 170°W). El Niño (or La Niña) is defined as 5 consecutive overlapping 3-month periods at or above $+0.5^\circ$ (or -0.5°). Classification: weak ($\pm 0.5^\circ$ to $\pm 0.9^\circ$), moderate ($\pm 1.0^\circ$ to $\pm 1.4^\circ$), strong ($\pm 1.5^\circ$ to $\pm 1.9^\circ$) and very strong ($\geq 2.0^\circ$)

Item	Weak	Moderate	Strong	Very strong
El Niño	2004–2005	2002–2003	–	2015–2016
	2006–2007	2009–2010		
	2014–2015			
La Niña	2005–2006	2011–2012	2007–2008	
	2008–2009		2010–2011	
	2016–2017			

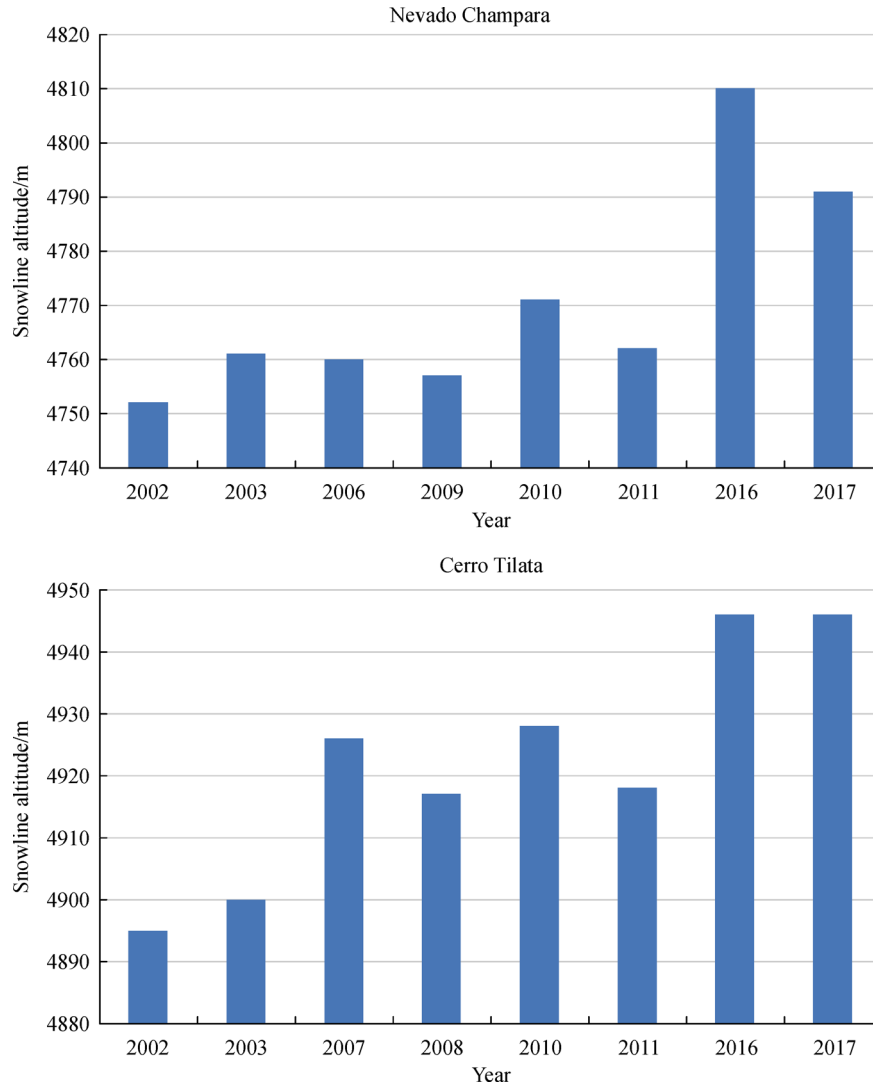


Fig. 2 Changes in snowline altitude since 2002.

observed that the fall in snowline altitudes was not enough to cover the rise occurred during the previous El Niño periods. There was a small fall in the snowline altitude of selected glacier of Nevado Champara in 2017 (La Niña) whereas no change was detected in the case of Cerro Tilata, possibly due to a delayed response in the eastern mountain ranges.

4.2 Glacier area changes between 2002 and 2017

Our results on glacier area changes also indicated a strong teleconnection with the El Niño and La Niña events, particularly on Nevado Champara (indicated in Fig. 3). After the two moderate El Niño events (2002/03 and 2009/10), there was a reduction in the area covered by snow and ice of Nevado Champara (19.4% and 13.45%, respectively). This reduction was, however, interrupted during the strong La Niña events in between and after (2007/08

and 2010/11) with a small increase in the snow/ice-covered areas (19.65% and 12.57%, respectively). Highest observed snow/ice area (8.83 km²) was observed soon after the strong La Niña conditions in 2008. Again after 2015/16, the strongest El Niño since 2000, the lowest area covered by snow/ice was observed (5.8 km²). Current weak La Niña condition was associated with a slight increase in snow-covered area between 2016 and 2017 (13.34%). It has to be noted that the overall trend in ice-covered areas in the studied peaks are decreasing (24.2%). Even though a similar trend was observed on Cerro Tilata during ENSO, the loss of glacier coverage was high (more than 45% between 2002 and 2017), which is similar to the observed trends in the entire eastern mountain ranges of Peru and Bolivia (Francou et al., 2003; Veetil et al., 2016b). However, initial size has to be taken into account because smaller glaciers in the tropical Andes are melting away at a faster rate since the late 1970s (Rabatel et al.,

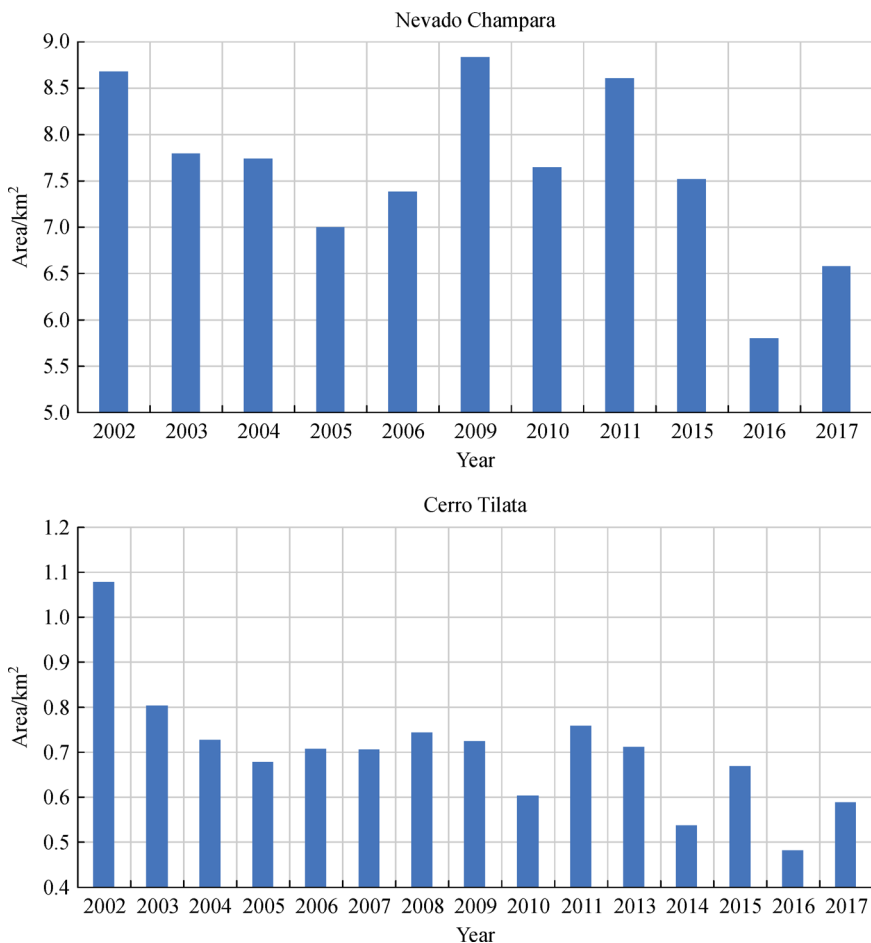


Fig. 3 Changes in glacier area since 2002.

2013; Veetil et al., 2017a). Estimated ± 1 pixel error for the delineated glacier boundaries varied between $\pm 2.1\%$ to $\pm 2.9\%$, which is within the acceptable limits.

5 Discussion

Glacier retreat in the tropical Andes since the 1970s and the influence of ENSO, particularly in 1997/1998, have been discussed in many previous studies (Arnaud et al., 2001; Francou et al., 2004; Veetil et al., 2014, 2016a, b, 2017a; Maussion et al., 2015). A few studies validated the relationship between ENSO and glacier mass balance in this region (e.g., Maussion et al., 2015). The 2015/16 El Niño has given an opportunity to investigate whether this relationship between glacier decline and ENSO still continues, which was the key objective of this study. Glacier surface changes and variations in snowline altitude indicated the influence of strong El Niño in 2015/16, which was analysed using $\delta^{18}\text{O}$ isotopes by Thompson et al. (2017). Variations in glacier area and snowline since 2002 showed distinct changes in these two glacier variables after this El Niño period. However, it should be noted that high

altitude tropical mountains continued to warm since the 1970s (Bradley et al., 2006) and this might have interfered with the short-term warming during the 2015/16 El Niño.

From the hydrological point of view, the results of this study have importance on water resources in Peru and Bolivia, during the dry season in particular. Rainfall is limited above 2500 m in these two tropical Andean countries and hence glacial meltwater play an important role in cities located above this elevation range (Rangecroft et al., 2013). Recent case studies from Bolivia (Soruco et al., 2015) and Peru (Bury et al., 2011; Baraer et al., 2012, 2015; Somers et al., 2016) support this observation. For example, in La Paz, the capital city of Bolivia, 27% of the dry season (austral winter) runoff for the period between 1963 and 2006 is estimated to originate from glaciers (Soruco et al., 2015). Similarly, a case study conducted in the Cordillera Blanca proposed that the reduction in annual average discharge due to the loss of glacierized regions can be between 2% and 30% (Baraer et al., 2012). However, due to the rapid melting of glaciers in Bolivia and Peru, a temporary increase in the dry season water availability is expected and once the glacier coverage disappears completely, dry season river discharge from the glacierized

catchments will be reduced (Huss et al., 2017; Vuille et al., 2018).

The current knowledge of the trends in glacier coverage in the tropical Andes and the contribution of glaciers on freshwater availability indicates the need for adaptation strategies to mitigate the impact of continuing decline in glacier coverage on regional communities. Glacial meltwater from the tropical Andean mountains has a key role in the economy of Bolivia and Peru. Agriculture, mining, and hydroelectric power generation are extremely dependent upon glacial meltwater in Peru (Vuille et al., 2018). The impact of a complete disappearance of glacier coverage on the economy of the region will be disastrous. Economic loss due to glacier-related hazards also needs to be considered while preparing adaptation strategies (Carey, 2005). Due to the rapid melting of glaciers, numerous glacial lakes were formed in Bolivia (Cook et al., 2016) and Peru (Chevallier et al., 2011; Veettil et al., 2017d). Such glacial lakes can be potentially dangerous for causing human and economic loss if a glacial lake outburst flood occurs.

Further studies are required to understand unknown factors, such as the influence of regional climate variations on glaciers in the tropical Andes, which may interfere with the impacts of ENSO. Socioeconomic changes and political conflicts due to glacier decline in Peru and Bolivia needs to be studied for the implementation of better adaptation strategies.

6 Conclusions

Results of this study support the hypothesis made in a recent review (Vuille et al., 2018) on the current state of glaciers in the tropical Andes that significant loss of glacier mass occurs during the El Niño events whereas La Niña conditions tend to lead to a slight mass gain or a balanced condition. From the changes in snowline altitudes and areas of glaciers considered, a strong teleconnection has been observed between glacial area loss and El Niño events, particularly in 2009/10 and 2015/16. Similarly, a small increase in ice-covered areas has been observed during the string La Niña events in 2007/08 and 2010/11. Observations on larger glaciers, such as the Quelccaya in Peru, supported this fact based on ice core studies (e.g., Thompson et al., 2017).

The loss of glacier surface depends on several factors such as initial area and altitude. Total surface loss during the study period for Nevado Champara, which has higher altitude and area compared to Cerro Tilata, was only 24% whereas that of Cerro Tilata was about 45%. The fluctuations in glacier surface and snowline were, however, more visible for Nevado Champara during strong El Niño and La Niña events, compared with (nearly) continuous changes in these variables shown by Nevado Champara in the eastern cordillera, which is far from the Pacific Coast.

However, further investigations are still needed for generalising our results – whether all glaciers in the tropical Andes showed similar patterns in surface loss or not during ENSO.

The results of this study indicate the importance of mountain glaciers in Peru and Bolivia as freshwater resources in the tropical Andes. Adaptation strategies are necessary to reduce the impact of continuing glacier decline on regional communities in this region.

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