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46 years of environmental records from the Nevado Illimani glacier group, Bolivia, using digital photogrammetry

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ABSTRACT. This study determines variations in ice extent of Nevado Illimani, Bolivia (16°38′ S, 67°44′ W), from 1963 to 2009. The results are compared with net accumulation rate variations obtained from a local ice core. We then propose an interpretation of the recent environmental history (last 46 years) of the region based on a study of remotely sensed and ice-core data. From 1963 to 2009, Nevado Illimani lost a total ice area of 9.49 ± 1.09 km^2, a 35% reduction. Area variations generally followed variations in net accumulation rates during this period. Despite the current glacier area reduction trend, the Nevado Illimani glaciers will not completely disappear in the next few decades.

1. INTRODUCTION

Tropical glaciers exist in South America (from Bolivia to Venezuela), Africa and Oceania (west Papua). The Andes mountain range is home to ~99% of these tropical ice masses (Kaser and Osmaston, 2002). Of the 2500 km^2 of tropical glaciers in South America, 70% are found in Peru, 20% in Bolivia and 10% in Ecuador, Colombia and Venezuela. In the tropics, the 0.1°C atmospheric isotherm remains practically at the same altitude throughout the year, allowing glacier front ablation at any time (Kaser and Osmaston, 2002), in contrast to glaciers at higher latitudes.

Mountain glacier distribution is controlled, fundamentally, by two factors: precipitation and altitude. Mountain ranges 'block' air-mass humidity, forcing precipitation, and promoting glacier-forming conditions. The second factor controls the equilibrium-line altitude (ELA), as glaciers will only form where the ELA is below mountain summits (Clapperton, 1993).

Some studies indicate that tropical glaciers are affected by regional climate variability. In the Andes, for example, glaciers exhibit a strong retraction during the positive phase of El Niño Southern Oscillation (ENSO) events (Francou and others, 2007). There is also evidence of strong glacial retraction for the past three decades along the full Andean mountain range due to atmospheric warming. This phenomenon reflects a glacial retraction rate increase and glacier thickness reduction, leading to the disappearance of many tropical glaciers (GTNH, 2010). The volume losses of mountain glaciers may be the clearest indicator of the rapid (if not accelerated) nature of climate change on a global scale (Francou and others 2005; Lemke and others, 2007).

There are many reasons to maintain interest in the study of Andean glaciers. They are important indicators of climate change. They also affect almost all the South American regional hydrologic regimes, particularly those that present dry seasons (e.g. southern Peru and Bolivia). In low-precipitation years, ice melt maintains minimum water flow levels, thus ensuring water supply to urban centres and hydroelectric power plants (Marengo and others, 2011).

This study determines ice extent variations at Nevado Illimani, Bolivia, from 1963 to 2009 using digital photogrammetry techniques. The results are compared with net accumulation rates obtained from ice cores extracted from the same ice mass (Ramirez and others, 2003). We then propose an interpretation of the recent environmental history (last 46 years) of the region based on the remotely sensed and ice-core data.

2. STUDY AREA

There are two main mountain ranges in Bolivia that are home to glaciers: the Cordillera Ocidental (Western Cordillera), which is formed by extinct volcanoes with crater glaciers and small isolated ice-covered peaks, and the Cordillera Oriental (Eastern Cordillera), with ~600 km^2 of glaciers. The Cordillera Oriental has four constituent parts: Apolobamba, Real, Muñecas and Tres Cruces/Nevado Santa Vera Cruz. Most types of glaciers are present, from ice caps and valley glaciers to small mountain glaciers (Jordan, 1998; Fig. 1). Our study site, Nevado Illimani, Bolivia (16°38′ S, 67°44′ W), is set within the mid-eastern sector of the Bolivian Andes, locally known as Cordillera Real. This mountain is 50 km south of La Paz and 180 km from Lake Titicaca. It is one of the oldest tertiary plutonic bodies in the westernmost sector of the Andes and is the product of lava intrusions. It has been greatly eroded by the La Paz river and its tributaries (Jordan, 1998). Its dimensions are ~10 km × 4 km, with some peaks over 6000 m a.s.l. (e.g. Pico del Indio, Pico Layco Kkollu). Twenty-six glaciers were selected to represent a comprehensive range of size, aspect and elevation.

Precipitation in this region occurs mainly during the austral summer (80% of annual precipitation), due to the humid air masses coming from the Amazon River basin (Vuille and others, 2003). In the dry season, corresponding to the austral winter (June–August), the prevailing wind directions are north and northwest. Extratropical precipitation events during the dry periods are attributed to the cold air masses flowing from Argentina, which originate from Antarctica. Vuille (1999) showed that in rainy seasons during El Niño events, the Bolivian Andes present negative precipitation anomalies. In La Niña years, the precipitation tends to be above average.

The decrease in precipitation during El Niño events delays snowpack formation. This, in turn, 'exposes' the glacial

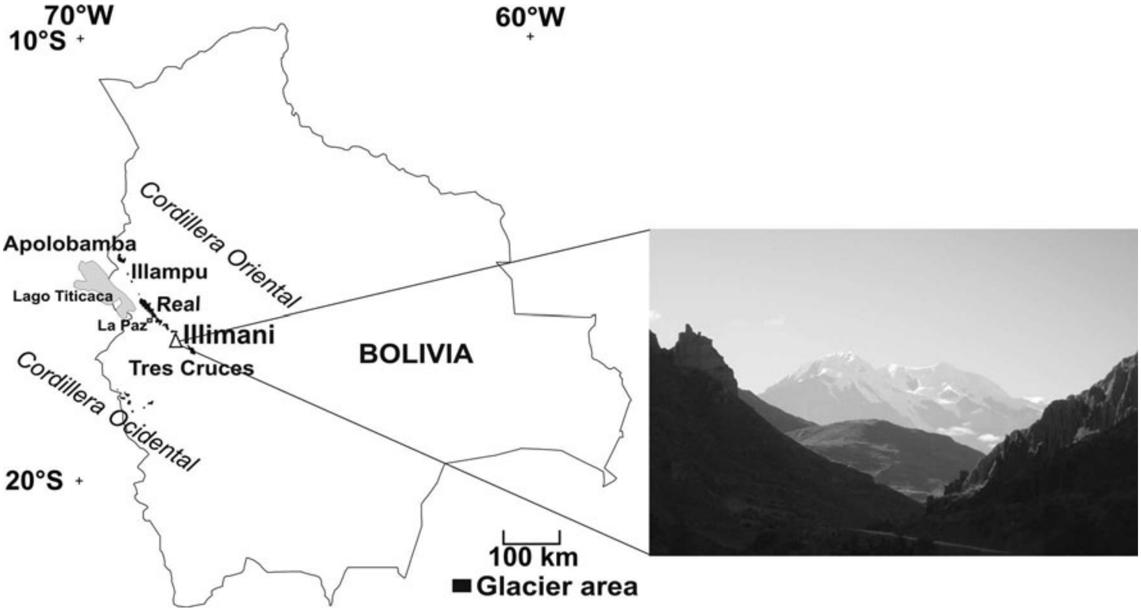

Fig. 1. Location of Nevado Illimani, Cordillera Real, Bolivia.

surface to solar radiation, promoting a more intense ablation process. According to Francou and others (2005), the glacial mass balance of the Bolivian Central Andes is strongly controlled by the ENSO phenomenon. During the positive phase, El Niño, precipitation can decrease by 10–30%, dry periods in summer are more frequent, and the air temperature increases by 1–3°C. In such periods, the ELA may increase, trending downwards during the negative phase (La Niña). This atmospheric temperature variability is the determining factor for the annual mass balance because the altitude at which snow melts rises with temperature increase. When the glacier accumulation zone is observed at higher altitudes (i.e. >5500 m a.s.l. in the Central Andes), glaciers can recover their ice masses in certain years. Therefore, information on both the snow precipitation volume and the liquid/solid phase over the total surface of the glacier is important. Small glaciers (<1 km^2 for the Central Andes) are clear examples of the influence of atmospheric temperature variability. In some years, the entire glacier surface can be converted into an ablation zone or an accumulation zone (Ramirez and others, 2001; Comunidad Andina, 2007). From 1974 to 1998, this region recorded an average atmospheric warming of 0.34°C per decade (Vuille and others, 2003); no precipitation trends were identified by these authors.

3. DATA

Aerial photographs

For the period 1963–83, we used aerial photographs from the Servicio Nacional de Aerofotogrametría (SNA), Bolivia, which were digitalized at 14 μm resolution. To orientate the images, we performed fieldwork in 2010 using a pair of Ashtech Zmax L2 differential GPS (DGPS) units to produce 22 control points on the terrain (Table 1).

Satellite images and digital elevation model

We used a set of ALOS PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping aboard ALOS) satellite images for the period 1983–2009. This sensor has three independent optical systems, allowing the production of stereo pairs, and offers data at nadir and from 24° lateral sightings (http://www.eorc.jaxa.jp/ALOS/en/about/prism.htm). The same control points were employed for orthocorrection and to generate a digital elevation model (DEM) using these images (Table 2).

Topographic data

Topographic data are derived from Jordan's (1990) map using air photographs taken in 1975.

Climatic database

We compared annual variations in precipitation at the El Alto/La Paz weather station (16.52° S, 68.18° W; 4070 m a.s.l.) with Illimani ice mass areal variations and net accumulation rates for the period 1960–98. El Alto is ~44 km to the northwest.

As discussed above, one of the main controls on the Bolivian glacier mass balance is the ENSO events. Thus we used the multivariate ENSO index (MEI), obtained from the Climate Diagnostic Center, Boulder, CO, USA, to examine

Table 1. Aerial photograph data and root-mean-square errors (RMSE)

Date	Scale	Number of photos	Direction of flight-line	RMSE m	Pixel resolution on the ground m
21 Jun 1963	1 : 29 200	8	northwest–southeast	1.67	1.00
27 Jun 1983	1 : 39 500	5	north–south	0.62	1.32

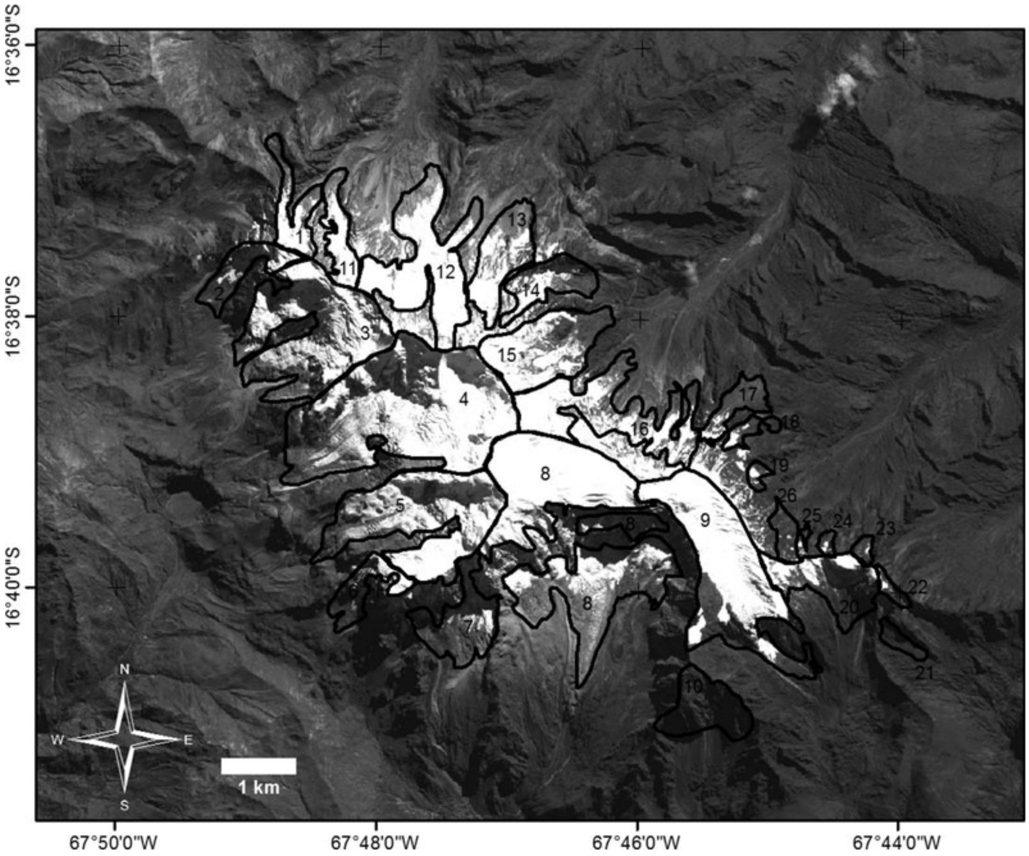

Fig. 2. Glacier limits of Nevado Illimani in 1963, drawn over an ALOS PRISM satellite orthoimage (1 June 2009). Numbers identify glaciers used in this study (as they do not have known names); see Table 3 for area and extent details.

whether changes in glacier area are associated with El Niño–La Niña events.

Ice-core data

In 1999, an international team led by the Institut de Recherche pour le Développement, France, recovered a 138 m ice core from Nevado Illimani (16°37′ S, 67°46′ W), at 6350 m a.s.l., providing information about the Amazon basin's atmospheric chemical composition and its evolution during the last century (Correia and others 2003; De Angelis and others 2003; Ramirez and others 2003). Hardy and others (2003) and Hoffmann and others (2003), comparing the regional meteorological data with the stable-isotope ratio (δ^{18}O) record in the Illimani ice core, concluded that precipitation rate variations are highly correlated to this ratio. They concluded that the stable-isotope ratios in the tropical Andes are more influenced by the precipitation rate than the atmospheric temperature.

4. METHODS

To quantify areal variations of Nevado Illimani glaciers from 1963 to 2009, we used aerial photographs (1963, 1983) and a set of satellite images (2009). To digitize ice-covered areas and drainage basins, photogrammetric restitution was performed using the Leica Digital System (LPS) and Planar 3D application. The drainage basins were identified for each glacier. In some periods, the higher limits of these basins were snow-covered, making visual identification less reliable, in which case a 1 : 70 000 scale topographic map (Jordan, 1990) was employed. This map was georeferenced based on the 2009 ALOS image. The vectorization of the glacier terminus was manually determined based on the aerial photographs and satellite imagery. Due to variable snow cover, co-registering differences and imagery resolutions, we considered a 5% error in the determination of each glacier area. We also used Jin and others' (2005) equation to determine the total error in the determination of the Illimani

Table 2. Satellite imagery and RMSE

Sensor	Date	Mode observation	Spectral resolution	Spatial resolution	RMSE	Resolution DEM	DEM vertical accuracy
			µm	m	m	m	m
ALOS PRISM	1 Jun 2009	Forward, nadir and backward views	0.52–0.77	2.5	1.25	10	±6.14

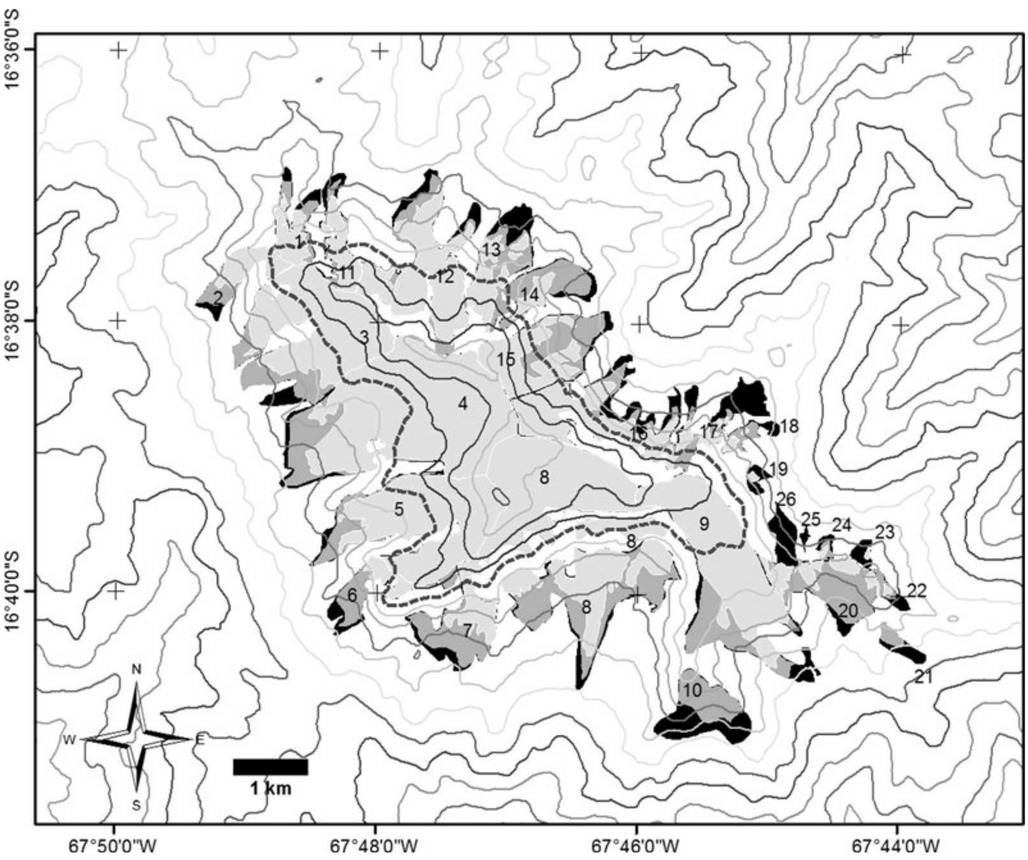

Fig. 3. Nevado Illimani area variations and glacier identification (numbers) with accumulation areas above 5600 m a.s.l. (dotted contour) for 2009 (light grey), 1983 (dark grey) and 1963 (black). Contour spacing is 100 m. Numbers identify glaciers used in this study (same as in Fig. 2); see Table 3 for area and extent details.

glacierized area in 1963, 1983 and 2009:

$$\text{Uncertainty} = \sqrt{(S_1 \times 5\%)^2 + (S_2 \times 5\%)^2 + \cdots + (S_n \times 5\%)^2},$$

where S_n is the glacierized area and n is the number of glaciers.

The plane areas on the 1963 and 1983 aerial photographs and the 2009 ALOS image made it possible to calculate the glacial retractions for the 46 year period (Fig. 2). Finally, we compared the area variations with the accumulation rate variations obtained from a Nevado Illimani ice core taken during a 1999 field campaign (Ramirez and others, 2003).

5. RESULTS

Area changes

Area changes in Nevado Illimani during the last 46 years are shown in Figure 3 and Table 3. We calculated that the glacier-covered area decreased from 27.4 km^2 to 17.9 km^2 from 1963 to 2009, a 35% areal reduction in 46 years. From 1963 to 1983, there was a 12% areal loss, and there was a twofold acceleration (–26%) from 1983 to 2009 (Table 4).

Aspect and elevation changes

In 1963, the mean terminus altitude for small glaciers (i.e. <1 km^2) was ~4722 m a.s.l. (Table 5); by 2009, it had risen by 348 m. For glaciers larger than 1 km^2, the termini rose 191 m from 4728 m. This difference may be attributed to the lower elevation of the accumulation areas; in some years the entire glacier surface of the smallest glaciers can be converted into an ablation zone.

Surface changes in glaciers show differences due to their slope orientation and solar-radiation exposure/mountain-face orientation (Table 6). The east-slope/north-face glaciers retracted more than the west-slope/south-face glaciers. The first group represented 46% of the glacial area in 1963, but only 30% by 2009. This may be related to variations in solar exposure. During the morning, the cloud cover is at lower altitudes, exposing the east-slope/north-face glaciers to direct solar radiation. In the afternoon, cloud cover rises to higher tropospheric elevations, enabling it to absorb greater radiation and leaving the west-slope/south-face glaciers more sheltered (Jordan, 1985). Thus, west-slope/south-face glaciers are larger in area than east-slope/north-face glaciers, allowing for ice mass recovery in years of positive balance.

6. DISCUSSION

Reasons for glacier variations

Figure 4 shows that there is some coherence between annual accumulation rates at Nevado Illimani and annual precipitation at the El Alto weather station. While there is no statistically significant trend in the El Alto precipitation for the period 1960–98, the accumulation rate at Nevado Illimani can be divided into two phases, 1960–81 and 1982–2000, with a decrease from $0.92 \pm 0.31\,\text{m a}^{-1}$ to $0.56 \pm 0.19\,\text{m a}^{-1}$.

From Figure 5, it is clear that El Niño events became stronger after 1982, coinciding with changes in the accumulation rate at Nevado Illimani.

Table 3. Variations in Nevado Illimani glacier-covered area

	Area			Area loss				
Glacier ID	1963	1983	2009	1963–83		1983–2009		since 1963
	km^2	km^2	km^2	km^2	%	km^2	%	%
1	0.43	0.39	0.25	0.04	9	0.14	36	42
2	0.49	0.42	0.30	0.07	14	0.12	29	39
3	2.48	2.36	1.95	0.12	5	0.41	17	21
4	4.16	3.98	3.62	0.18	4	0.36	9	13
5	2.33	2.29	2.02	0.04	2	0.27	12	13
6	0.45	0.37	0.15	0.08	18	0.22	59	67
7	0.87	0.78	0.33	0.09	10	0.45	58	62
8	4.23	4.03	3.28	0.20	5	0.75	19	22
9	2.54	2.26	1.88	0.28	11	0.38	17	26
10	0.77	0.37	0.00	0.40	52	0.37	100	100
11	0.46	0.37	0.30	0.09	20	0.07	19	35
12	1.78	1.62	1.32	0.16	9	0.30	19	26
13	0.82	0.66	0.26	0.16	20	0.40	61	68
14	0.59	0.52	0.13	0.07	12	0.39	75	78
15	1.27	1.19	0.73	0.08	6	0.46	39	43
16	1.63	1.31	1.01	0.32	20	0.30	23	38
17	0.36	0.10	0.06	0.26	72	0.04	40	83
18	0.15	0.11	0.03	0.04	27	0.08	73	80
19	0.08	0.01	0.01	0.07	88	0.01	88	88
20	0.91	0.81	0.28	0.10	11	0.53	65	69
21	0.15	0.07	0.00	0.08	53	0.07	100	100
22	0.11	0.06	0.01	0.05	45	0.05	83	91
23	0.08	0.01	0.01	0.07	88	0.00	100	88
24	0.06	0.04	0.01	0.02	33	0.03	75	83
25	0.02	0.01	0.00	0.01	50	0.01	100	100
26	0.21	0.00	0.00	0.21	100	0.00	100	100
Total	**27.43**	**24.14**	**17.94**	**3.29**	–	**6.20**	–	–

Table 4. Nevado Illimani rate of change

Year	Variation in area	Variation rate	Rate of change
	km^2	%	km^2 a^{-1}
1963–83	–3.29 ± 0.78	–12	–0.17
1983–2009	–6.20 ± 0.69	–26	–0.24
1963–2009	–9.49 ± 1.09	–35	–0.21

Table 5. Variations in the number of glaciers in Nevado Illimani and glacier terminus average elevations

Glacier class	Number of glaciers		Mean elevation of terminus	
	1963	2009	1963	2009
km^2			m	m
<0.05–0.09	4	7	4722	5070
0.10–0.49	8	8	4889	5061
0.50–1.00	6	1	4820	4885
>1.00	8	6	4728	4919
Total	**26**	**22**	–	–

Glacier variation and ice-core data

Figure 6 compares the Nevado Illimani glacier area losses from 1963 to 2009 with the net accumulation rate from an ice core at the same ice mass. It is clear that the mass loss rate during this period increased after 1983 (i.e. 3.3 ± 0.78 km^2 from 1963 to 1983, then 6.2 ± 0.69 km^2 from 1983 to 2009). Concomitantly, the accumulation rate decreased, mainly from 1983 onwards.

The observed ice mass reduction may be a result of the observed precipitation rate decrease (which also implies a smaller surface albedo), a reduction in cloud cover and an increase in air temperature (which would increase the sublimation rate at the Nevado Illimani altitude) (Comunidad Andina, 2007).

At Nevado Illimani, the smaller glaciers (<1 km^2) have experienced the greater proportional areal reductions (∼76% from 1963 to 2009; Table 3). These results are similar to those

Table 6. Relation between glacier aspect and Nevado Illimani glacier-covered area

Year	Orientation			
	North		South	
	km^2	%	km^2	%
1963	13.5	46.5	15.8	53.5
2009	5.6	30.5	13.0	69.5

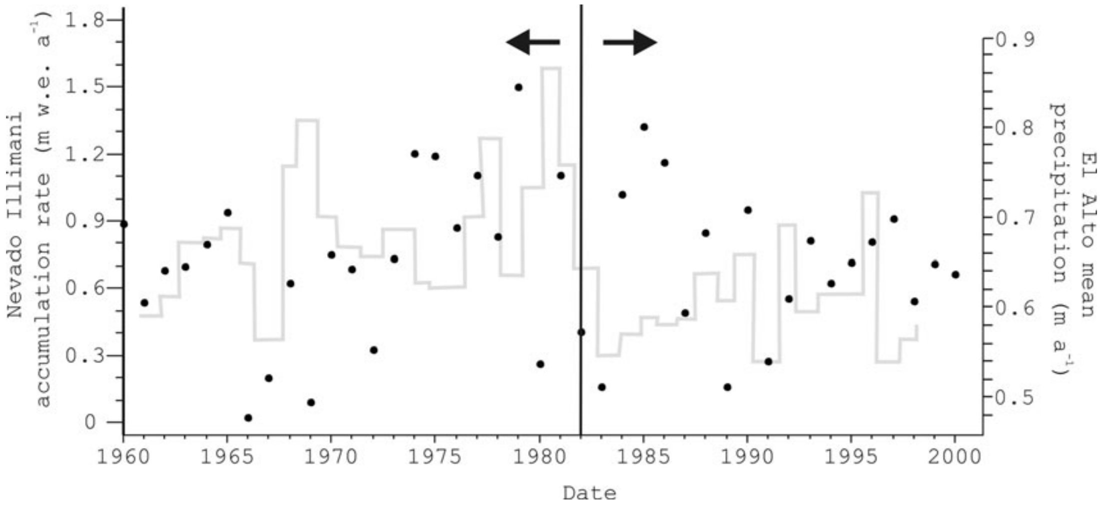

Fig. 4. Nevado Illimani accumulation rate (grey histogram) and mean annual precipitation trend at the El Alto weather station (black dots). The vertical line in the middle of the graph divides the accumulation at Illimani into two phases, 1960–81 and 1982–2000, with a decrease from 0.92 m a^{-1} to 0.56 m a^{-1}.

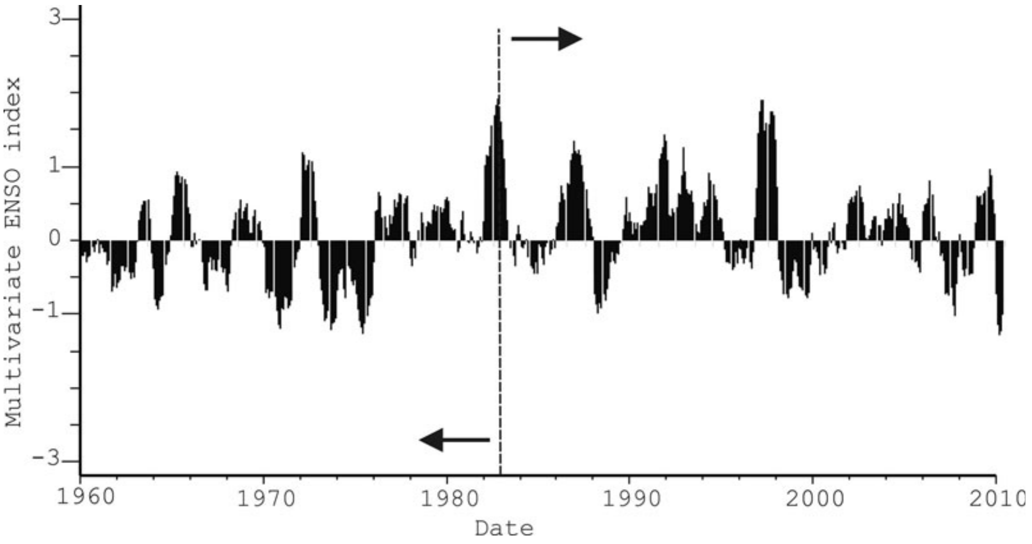

Fig. 5. Multivariate ENSO index (MEI) from 1960 to 2010. The dashed line separates two distinct periods: La Niña events predominated until the 1980s; afterwards, El Niño events became more frequent.

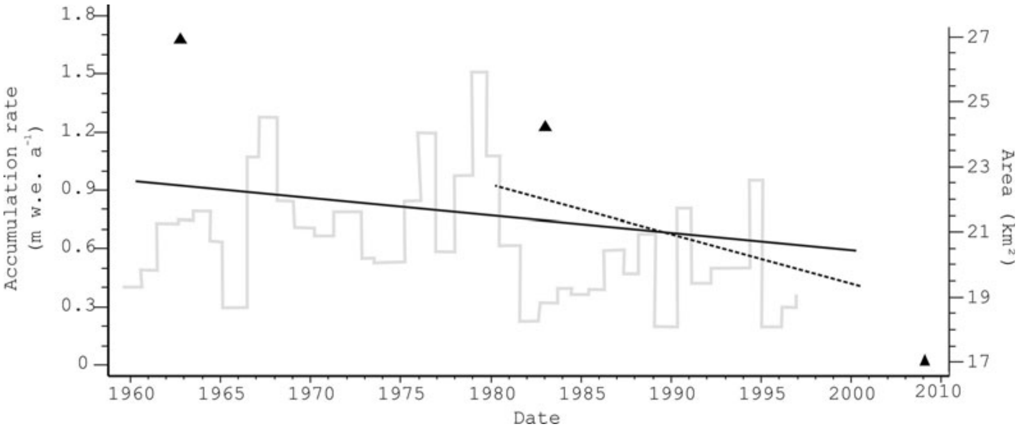

Fig. 6. Variation in Nevado Illimani's net accumulation rate, as determined from a local ice core (obtained at 6350 m a.s.l.), against the loss in area defined by this study. Triangles (glacier area), grey line (accumulation rate). The continuous black line marks the accumuation rate trend at the Illimani from 1960 to 1998 (0.92 m a^{-1} w. eq.) and the dotted line marks the same trend from 1983 to 2000 (0.562 m a^{-1} w. eq.).

found at other Bolivian glaciers: Glaciar Zongo (16° S, 68° W), by tropical standards a large glacier, had an area of 2.29 km^2 in 1963 but from 1956 to 2006 lost 14.4% of its area and has been rapidly shrinking since 1975 (Soruco and others, 2009); and Glaciar Chacaltaya (16°20′ S, 68°07′ W), a small glacier, had an area of 0.195 km^2 in 1963 (Ramirez and others, 2001) but had disappeared by 2010 (WGMS, 2011).

We do not expect the complete disappearance of the Nevado Illimani ice mass in the near future. Of the glaciers surrounding this mountain (Fig. 3), six (glacier ID: 3, 4, 8, 9, 11 and 12) have 40% of their glacial accumulation areas above 5500 m. Thus, it possible for Nevado Illimani to recover its ice mass in certain years. In 2007/08, Glaciar Zongo had a mass balance of +257 mm w.e. (WGMS, 2011).

7. CONCLUSIONS

In total, Nevado Illimani lost 9.49 ± 1.09 km^2 of its glacier area from 1963 to 2009. This reduction occurred in two phases: ~12% from 1963 to 1983, and a further 26% in the following 26 years (up to 2009). The number of glacier basins has also reduced since 1963, from 26 to 22. East-slope/north-face glaciers have shown a greater retreat than those set on the west/south face of the mountain.

By comparing these results with accumulation rates, determined from a local ice core, we identified a marked reduction from 1983 onwards that may be the main factor in the increasing glacier retreat at the Nevado Illimani site.

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