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Spatio-temporal mapping of glacier fluctuations in the subtropical Central Andes: Case studies of Alto Del Plomo and Volcan Maipo

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ABSTRACT

Glaciers located in the Subtropical Central Andes region, play an important role in the surrounding hydrological system due to their significant contribution to the runoff of Andean rivers. Furthermore, they constitute a natural water reservoir that can buffer the impact of meteorological droughts seasons on socioeconomic activities in the region. The Intergovernmental Panel on Climate Change (IPCC (2013)) has concluded that glaciers have clearly shrunk at global scale. Nevertheless there is a need to quantify variations at a local-to-regional scale. In this interdisciplinary work we make use of the Geographic Information System tool in a climatic study with the purpose of visualizing spatial and temporal changes in glaciers' extension through a multi-temporal analysis of satellite images in the period 1989–2015. Two glaciers in the Subtropical Central Andes region were selected: Alto del Plomo glacier (32.98°S–70.01°W) in the Plomo river basin and Volcán Maipo glacier (34.16°S–69.8°W). The accumulation zones for both glaciers are found at similar altitudes and distant only by less than 130 km, but they have different morphological characteristics and the Volcán Maipo glacier is located within a protected area in the natural reserve of Laguna del Diamante. The results of the analysis indicate a decrease in the total area (18%) of Alto del Plomo glacier that is especially evident in its glacier tongue. In contrast, the Volcán Maipo glacier presented almost no change in the 27-year period considered. The climate factors, temperature and nival precipitation, that affect the evolution of the areal extent of the glaciers do not seem to fully explain the different behavior seen in these two glaciers. It is suggested here that the environmental factors that surround them might explain the observed behavior.

1. Introduction

The Subtropical Central Andes of Argentina and Chile (between 30° and 37°S) feature some of the highest peaks of the mountain range, such as mount Aconcagua (6961 m), Tupungato (6570 m), Maipo (5323 m), Mercedario (6770 m). Several of the high peaks have glaciers, which are the sources of many of the main rivers that flow through Chile to the Pacific Ocean and through Argentina to the Atlantic Ocean. West of the Andes, 8.4 million Chilean inhabitants live in the metropolitan region, 55% of Chilean population (INE, 2003). On the Argentinean side a large fraction of the population (~2.4 million people, INDEC, 2010) lives in the productive oasis of the Mendoza province, associated with the San Juan, Mendoza, Tunuyan, Diamante and Atuel river basins. Water availability in this arid region, for human consumption and for economic activities –irrigation, industry and hydropower generation-, is the result of stream flow mainly fed by seasonal snow melt and, to a lesser extent, by the contribution of glacier melting (Le Quesne et al., 2009). As a consequence, mountain glaciers constitute a key hydrological reservoir for the region. In their absence, rivers would depend exclusively on seasonal snow cover, which is highly variable and can be virtually zero in severely dry years (see Fig. 2 from Masiokas et al., 2006).

Several studies have focused on the behavior of glaciers in the region using different sources of information, such as historical records, photographs, satellite images, etc. Masiokas et al. (2009) provides a review of the literature that describes glacier evolution in the extratropi-

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cal Andes over the last 1000 years, highlighting the generalized retreat and a significant mass loss. In a recent study, Malmros et al. (2016) also shows a general retreat in glaciers in the central Andes of Argentina and Chile, between 32°9′ and 33°4′S in the period 1955–2013/2014, using aerial photography and satellite images from Landsat and Advanced Spaceborne Thermal Emission and Radiometer (ASTER).

The main objective of the present work is to provide an updated description of the spatio-temporal evolution of two glaciers in the Subtropical Central Andes region: Alto del Plomo and Volcán Maipo, with accumulation zones at 5200 m and 5300 m, respectively, but with different geomorphological characteristics. Furthermore, the meteorological factors that may have influenced their evolution are explored. In this paper we provide an interdisciplinary approach in a climatic study with the inclusion of the Geographical Information System tool, that is used to enter, collect, handle, perform calculations, statistical analysis and obtain georeferenced data, integrating different sources of geographical information. With this tool we have performed a multi-temporal analysis with the purpose of studying the evolution of glacier areas both spatial and temporally. This work presents an updated spatio-temporal monitoring and estimates of the areal extent of two glaciers over 27 years. Section 2 provides a description of the region and the particular two glaciers selected for this study, as well as the data and the methodology employed for the analysis. Results are presented in Section 3 and the discussion of results and general conclusions are presented in Section 4.

2. Data and methodology

2.1. Description of the selected glaciers

Two glaciers were selected for this study – Alto del Plomo and Volcán Maipo- and Fig. 1 shows their location in the Subtropical Central Andes, both in the province of Mendoza, Argentina. The Alto del Plomo glacier is located in the Plomo river basin (32.98°S – 70.01°W), has a southern orientation and is part of the largest glacier system located in the Subtropical Central Andes of Argentina. Following the primary classification of Rau et al. (2005), Alto del Plomo glacier is characterized by a well-defined accumulation area and its tongue is channeled and flows down the valley. This glacier system has been extensively studied and detailed information about its position dates back to 1909 (Llorens and Leiva, 1995). In 1909 the system identified as “Glaciar del Plomo” from a terrestrial photogrammetric survey of the area carried out by Helbling (1919), was formed by the following glaciers: Alto del Plomo, Bajo del Plomo, Oriental del Juncal and Grande del Juncal. Between 1909 and 1934, the system of “Glaciar del Plomo” retreated 1580 m and the thickness of its terminal zone also diminished considerably (Espizua, 1986). By 1955, the glaciers of the system separated and the Alto del Plomo glacier was identified as a separate glacier; this glacier originates at 5200 m and is one of the foci of this study. Since then, Alto del Plomo further receded 70 m by 1963 and an additional 290 m by 1974. Llorens and Leiva (1995) analyzed aerial photographs from 1974 and Landsat images from sensors MSS and TM, for the period 1982–1991. They showed that between 1974 and 1982 its main front has retreated 200 m, while a large ice remnant separated from the main front, and diminished by approximately 530 m in length and 200 m in width. It is evident from Fig. 5 in Llorens and Leiva (1995) that by 1991 the front of Alto del Plomo had continued to retreat.

The Volcán Maipo caldera is located in the protected area of Laguna del Diamante in the province of Mendoza, Argentina (34.16°S–69.8°W, Fig. 1), and it is covered by ice and permanent snow at 5323 m (Alonso and Trombotto, 2012). The nature reserve was created in 1994 to protect and preserve flora, fauna, landscape, wetlands, glaciers and archaeological and paleontological material in the area. The Volcán Maipo glacier is a mountain glacier type that, as defined by Müller et al. (1977), are generally small in size, confined by the topography of the mountainous terrain and do not flow through a valley. This category of mountain glacier type includes cirque, niche and crater glaciers. Alonso and Trombotto (2012) describe the geomorphological characteristics of the Volcán Maipo glacier but there are no studies in the literature on the temporal evolution of this glacier.

The climatic characteristics of the Subtropical Central Andes are markedly different east and west of the mountain range. During austral winter, the subtropical Pacific high weakens and migrates northward (Satyamurty et al., 1998), enhancing the westerly flow through central Chile and favoring frontal activity. This determines that maximum precipitation occurs in winter in central Chile and over the mountains (Aceituno, 1988; Garreaud et al., 2009). Due to its North-South orientation and its elevated mean altitude at this latitude, the Andes acts like a topographic barrier preventing the humidity from the Pacific Ocean from reaching the eastern slopes and the lowlands in Argentina. Precipitation in this region of Argentina is mainly due to summer convection, thanks to the contribution of humidity by the low level jet from the Atlantic Ocean and the Amazon basin (Vera et al., 2006). Different authors (Aceituno, 1988; Rutlland and Fuenzalida, 1991; Compagnucci and Vargas, 1998; Montecinos and Aceituno, 2003) relate climate variability in this region with El Niño – Southern Oscillation (ENSO). Particularly relevant to this study, Escobar and Aceituno (1998) analyzed the relationship between winter snowfall and El Niño, using data from snow accumulation stations over the subtropical Andes between 30° and 38°S, for the period 1951–1997. They found anomalously large snow accumulation between 30°–35°S during El Niño events and the opposite behavior during La Niña events. Masiokas et al. (2006) also showed an ENSO-related influence on snowpack in the central Andes of Argentina and Chile, mainly concentrated during the austral winter months.

2.2. Datasets

2.2.1. Satellite images

Landsat images have been widely used to delimitate glaciers in different parts of the world (e.g.: Paul, 2002; Le Quesne et al., 2009; Burns and Nolin, 2014; Kumar et al., 2014). For this study, satellite images from Landsat, were used, specifically from the following sensors: i) Thematic Mapper (TM), ii) Enhanced TM Plus (ETM+) and iii) Operational Land Imager and Thermal Infrared Sensor (OLI-TIRS). All three sensors have a spatial resolution of 30 m. The TM and ETM+ sensors have the same spectral bands, but the spectral width is different for equivalent bands in OLI-TIRS. A detailed description of the different sensors is available on the Landsat webpage: http://landsat.usgs.gov/.

The images were selected and downloaded from the United States Geological Survey website (http://glovis.usgs.gov). They were already georeferenced and ortorectified with the global reference system WGS84 and projected with Universal Transversal Mercator (UTM). The images considered in this study were all taken between mid-March and the beginning of April, corresponding to the end of the ablation season, when seasonal snowpack has already melted in this region, as recommended by Paul et al. (2009). Ice and clouds have maximum reflectivity in the same regions of the electromagnetic spectrum, so glaciers and snow are not discernible from clouds. Table 1 shows the list of images selected for the present study. The percentage of cloud cover over the entire scene is indicated, but none of them have cloud cover over the selected glaciers. Note that in spite of the restrictions for the selection of images, we were able to obtain time series for each glacier with temporal gaps of less than three years, which allows us to explore their interannual variability. Due to the difference in spectral bands between

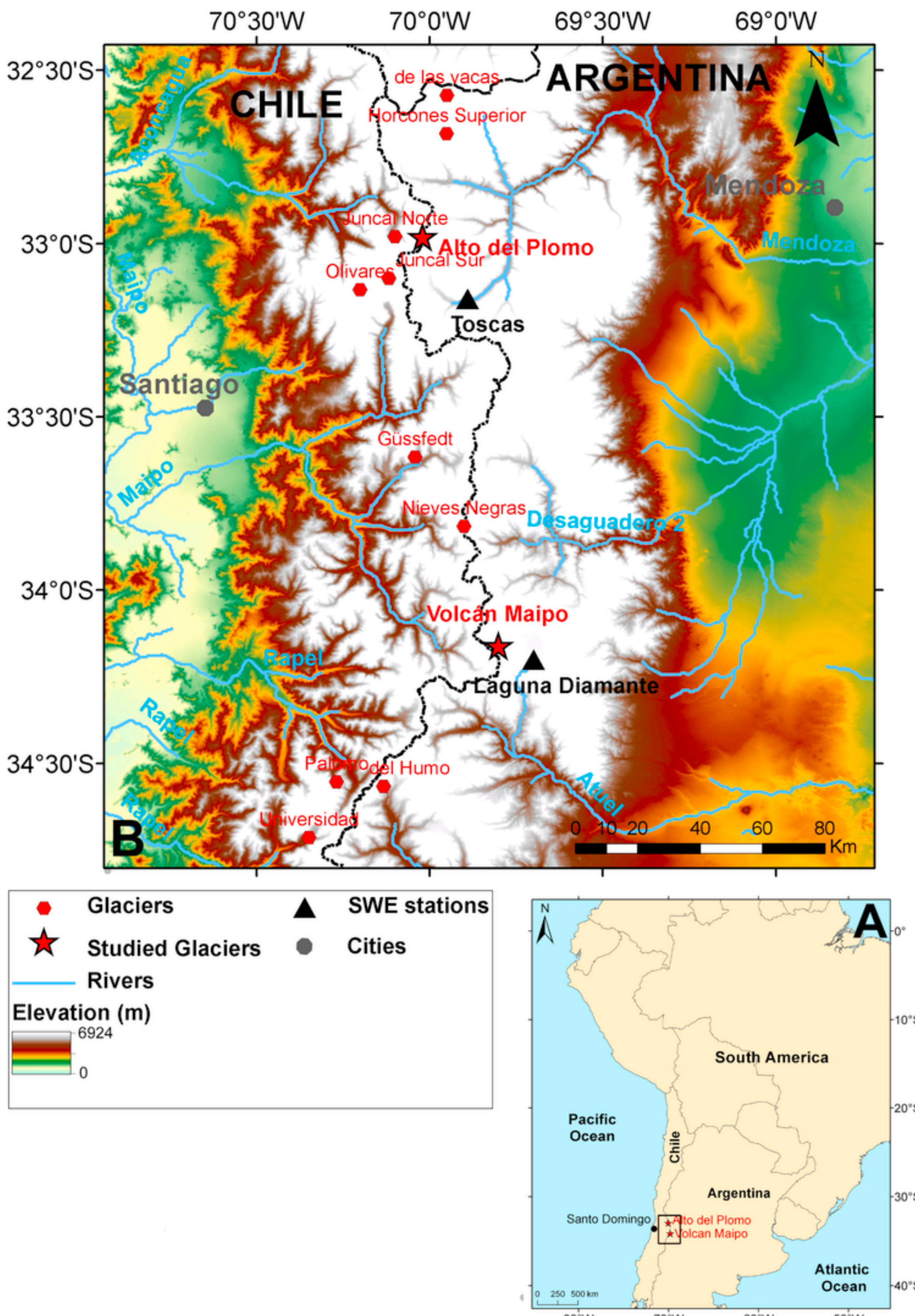

Fig. 1. (A) Location of the region of study (black rectangle) within South America, indicating the location of the two glaciers evaluated in this study and of the Santo Domingo radiosonde station. (B) Topography, location of some of the glaciers in the region (red dots) and Snow Water Equivalent (SWE) stations used (black triangles). The studied glaciers are highlighted with red stars. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sensors, the methodologies applied here take this difference into account. Table 2 shows the wavelengths of the selected bands of each sensor used in the present study.

2.2.2. Climate data

Since the main source of mass for glaciers is snowfall, we have evaluated the behavior of this variable in the region, as it relates to glacier advances and retreats. Snow Water Equivalent (SWE) data from snow pillows from the Subsecretaría de Recursos Hídricos de la Nación Argentina, were used in this study. The stations closest to the studied glaciers were selected: Toscas (33.16°S, 69.89°W, 3000 m) in the vicinity of Alto del Plomo glacier and Laguna Diamante (34.2°S, 69.7°W, 3250 m), next to the Volcán Maipo glacier. Note that both stations are located at similar heights, but at lower elevation than the glaciers' accumulation zone. Due to the fact that the stations measure snow ~2000 m downhill of the accumulation zones, they will underestimate the accumulated mass. However, in this paper we analyze the interannual variability and trends of the SWE, and not the absolute value. The location of the stations can be seen in Fig. 1B. Monthly SWE data were available from the period 1989–2015, coinciding with available images from Landsat for these glaciers.

Table 1
List of Landsat images used in the present study. Alto del Plomo glacier is located within scene 233/083 and Volcán Maipo glacier is located within scene 232/084.

Scene	Image ID	Date of acquisition	Satellite	Sensor	Cloud cover (%)
	LT42330831989076XXX01	17/03/1989	Landsat-4	TM	10
	LT52330831993079CUB00	20/03/1993	Landsat-5	TM	32
	LT52330831995085CUB00	26/03/1995	Landsat-5	TM	22
	LT52330831996088CUB00	28/03/1996	Landsat-5	TM	17
	LT52330831999064COA00	05/03/1999	Landsat-5	TM	26
	LE72330832000091EDC00	31/03/2000	Landsat-7	ETM+	3
233/083	LE72330832002080EDC00	21/03/2002	Landsat-7	ETM+	5
	LT52330832004078CUB00	18/03/2004	Landsat-5	TM	0
	LT52330832006099COA00	09/04/2006	Landsat-5	TM	23
	LT52330832009091COA02	01/04/2009	Landsat-5	TM	1
	LT52330832010078CUB00	19/03/2010	Landsat-5	TM	0
	LT52330832011081COA01	22/03/2011	Landsat-5	TM	16
	LC82330832015076LGN00	17/03/2015	Landsat-8	OLI-TIRS	6.68
	LT52320841989093CUB00	03/04/1989	Landsat-5	TM	39
	LT52320841990080CUB00	21/03/1990	Landsat-5	TM	18
	LT52320841993088CUB00	29/03/1993	Landsat-5	TM	8
	LT52320841995078CUB00	19/03/1995	Landsat-5	TM	21
	LT52320841996081CUB00	21/03/1996	Landsat-5	TM	1
	LT52320841999105COA00	15/04/1999	Landsat-5	TM	4
232/084	LE72320842000084COA00	24/03/2000	Landsat-7	ETM+	1
	LT52320842001078COA00	19/03/2001	Landsat-5	TM	22
	LT52320842004087COA00	27/03/2004	Landsat-5	TM	11
	LT52320842007079CUB00	20/03/2007	Landsat-5	TM	0
	LT52320842010087CUB00	28/03/2010	Landsat-5	TM	35
	LT52320842011090COA01	31/03/2011	Landsat-5	TM	1
	LC82320842015069LGN00	10/03/2015	Landsat-8	OLI-TIRS	1.03

Table 2
Band widths (μm) of selected Landsat bands from sensors used in this study (Source: http://landsat.usgs.gov/).

TM	Band width (μm)	ETM+	Band width (μm)	OLI-TIRS	Band width (μm)
Band 4	0.76–0.90	Band 4	0.77–0.90	Band 5	0.85–0.88
Band 5	1.55–1.75	Band 5	1.55–1.75	Band 6	1.57–1.65
Band 7	2.08–2.35	Band 7	2.09–2.35	Band 7	2.11–2.29

Additionally we explore temperature trends in the vicinity of the studied glaciers. We use temperature data from the Climate Research Unit (CRU), University of East Anglia high resolution gridded dataset version 3.23 (Harris et al., 2014). It is a monthly dataset covering the period 1901–2014 with a spatial resolution of 0.5×0.5°. We select the closest points to Alto del Plomo and Volcán Maipo and explore temperature trends in the period 1989–2014 for every season. In order to explore the influence of the vertical structure of temperature, we also analyze the height of the 0° isotherm. Daily radiosonde data were downloaded for this analysis from the webpage of the University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html) for station Santo Domingo (33.65°S, 71.61°W, 75 m). The location of the station relative to the studied glaciers can be seen in Fig. 1A. We calculate the monthly time series of the height of the 0° isotherm for the period 1989–2015, following the methodology of Rusticucci et al. (2014). We also compute seasonal trends for this variable.

2.3. Methods of analysis

The ratio of bands TM 4 and 5 is used to delineate the glaciers, a methodology widely used in the literature to identify glaciated areas (e.g.: Hall and Chang, 1988; Bayr et al., 1994; Paul, 2002; Bown et al., 2008). Furthermore, Albert (2002) evaluated 11 methods and concluded that ratio of TM bands 4 and 5 is the most cost-effective method for determining ice-covered area. This method provides very accurate results for debris-free ice (Paul and Andreassen, 2009), but it also the most effective when dealing with problematic areas such as debris-covered ice (Albert, 2002). In this paper we only map debris-free ice of the glacier in every image. For images from the OLI-TIRS sensor, we tested the ratio of bands 5 and 6, with similar wavelengths to TM bands 4 and 5. Glacier outlines were obtained by using the 1.5 value as the best threshold from the band ratios that allow us to separate areas with high values, corresponding to pixels covered by ice or snow that were identified in the false-color composites. This methodology provided an automated method for the delimitation of ice bodies and the calculation of its area through a Geographic Information System.

Glacier boundaries were manually corrected to isolate the debris-free parts of the glaciers. Volcán Maipo glacier was identified following Alonso and Trombotto (2012) that provided a geomorphological map from an ASTER image and corroborated by field work. We also followed the identification from the Argentinean glacier inventory (IANIGLIA, 2015) for both glaciers. From the Argentinean glacier inventory maps, it can be seen that the Volcán Maipo glacier does not have debris-covered parts, while the Alto del Plomo glacier presents debris-cover only in its terminal tongue. Moreover, we use contrast-enhanced SWIR false-color composite (FCC) with TM and ETM+ bands 4, 5 and 7 (as red, green, blue) and with OLI-TIRS bands 5,6 and 7 (as red, green, blue) in the background. This composite enhances snow and ice surfaces in red (Philip and Ravindran, 1998; Haq et al., 2012). Google Earth high-resolution images provided additional information to perform the correction of glacier outlines. This process can be crucial in the location of terminus position of glaciers, since it can differ by several hundred meters if glacier outlines were digitized by different analysts (Paul et al., 2013). In the present work, all the glacier outlines were corrected by the same analyst, so the change analysis should be reliable, as recommended by Minora et al. (2016).

The delimitation of glacier outlines through satellite images have inaccuracies mainly related to image resolution and to the meteorological and environmental conditions at the time of acquisition such as the seasonal snow cover, clouds and debris cover (D'Agata and Zanutta, 2007; Paul and Andreassen, 2009; Sarikaya, 2012; Minora et al., 2016). All images were acquired at the end of the ablation period, without seasonal snow outside the glaciers, as recommended by Paul (2009). Furthermore, only images free of clouds over the glaciers of interest were selected. In consequence, we assume that these sources of inaccuracies are negligible. We only digitalized debris-free glaciers, so following Paul and Andreassen (2009) we assume an error of 10%. A similar estimate of the error was considered by Sarikaya (2012) for the study of Mount Agrı Ice Cap in Turkey.

3. Results

3.1. Variations in glacier area

Fig. 2 shows the digitalized outlines for the Alto del Plomo glacier in FCC images taken during the years 1989, 2000 and 2015, in which the red color corresponds to surfaces covered by ice. This glacier originates in the peaks of mounts Rio Blanco, León Blanco and León Negro at approximately 5200 m height, and flows southward (Espizua, 1986). The different outlines -from 1989, 2000 and 2015- show that its tongue gets narrower with time. The large ice remnant in the southern tip, separated from the main front, that is present in 1989, has disappeared by the year 2000. It is also evident that between 1989 and 2000, the accumulation area has diminished, especially in the west and northwest sectors.

Similarly, Fig. 3 shows three outlines of the Volcán Maipo glacier for the same years: 1989, 2000 and 2015. The glacier originates in the peak of the Volcán Maipo at 5323 m and the main glacier flows south and southeast. Between 1989 and 2000 there is not much change in glacier areal extent. In the northern sector, the accumulation area was larger in 2000 than in 1989. The southwest tongue remained stable between 1989–2015, while its terminus position shows a slight retreat in 2015. Larger differences are evident in the southeastern front, presenting an important retreat in 2015.

In order to quantify the variation in the outline of each glacier as a function of time, we calculate the total area for each glacier from all the images listed in Table 1, resulting in a time series of the areal extent. Fig. 4 shows these time series of glaciated areas from glaciers Alto del Plomo and Volcán Maipo, where it is evident that they have a very different behavior over this 27-year period. Volcán Maipo glacier presents little variation and a reduction of only -0.19 ± 0.02 km^2 between 1989 and 2015, about 4.2% loss. In contrast, Alto del Plomo

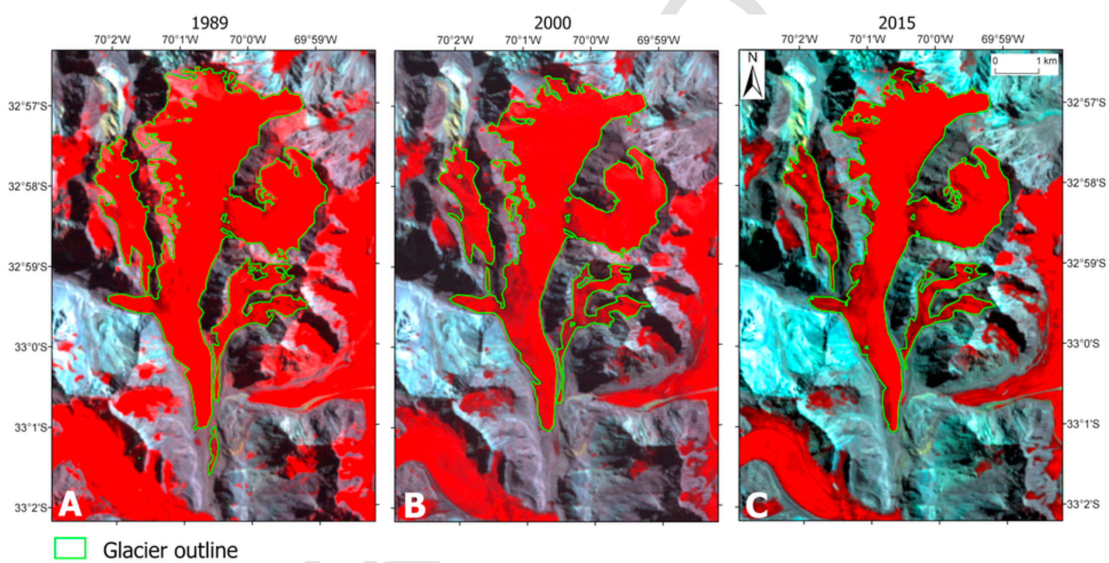

Fig. 2. Digitized outlines of Alto del Plomo glacier from Landsat images false-color composites (RGB = Bands457) for: (A) 1989 Sensor TM, (B) 2000 Sensor ETM+, and Landsat image false-color composites (RGB = Bands 567) and (C) 2015 Sensor OLI-TIRS.

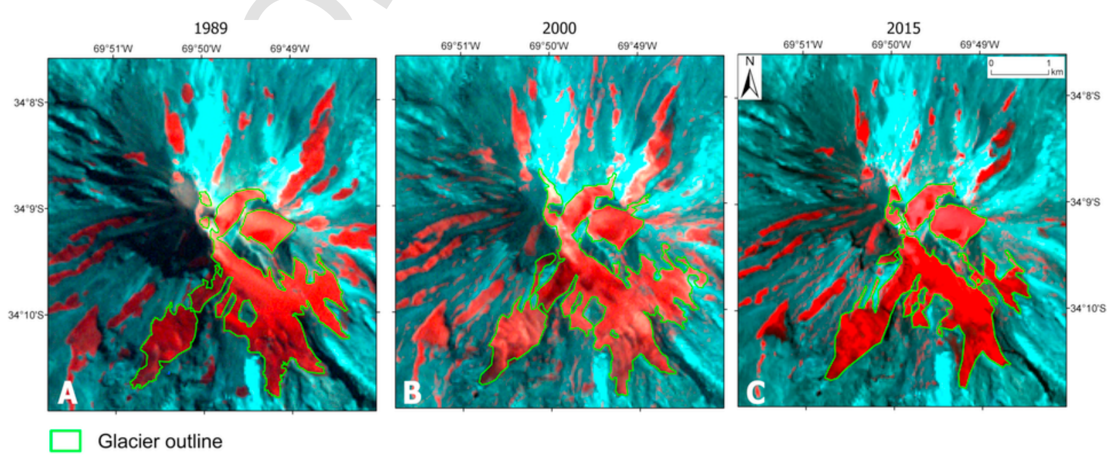

Fig. 3. Digitized outlines of Volcán Maipo glacier from Landsat images false-color composites (RGB = Bands457) for: (A) 1989 Sensor TM, (B) 2000 Sensor ETM+, and Landsat image false-color composites (RGB = Bands 567) and (C) 2015 Sensor OLI-TIRS.

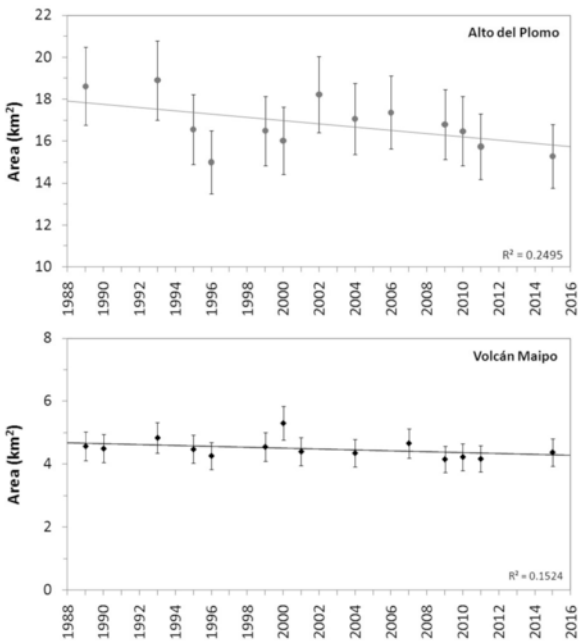

Fig. 4. Time series (symbols) and linear fit (line) of glacier area (km^2) for the period 1989–2015 corresponding to Alto del Plomo (upper panel) and Volcán Maipo (lower panel). The value of R^2 is indicated in each panel.

glacier shows a marked decrease in its total area, resulting in an area loss of 3.34 ± 0.33 km^2 between 1989 and 2015, corresponding to ~18% of its total area in 1989. It is interesting to note that Alto del Plomo glacier suffered from a very fast decrease between 1993 and 1996, which is much less pronounced in the area of Volcán Maipo glacier. And furthermore, some years with decrease in area of Alto del Plomo glacier correspond to area increase (2000) or no change in Volcán Maipo glacier (2009–2011). In the next sub-section we explore the variability of climatic variables that may help understand the different evolution.

3.2. Meteorological and climatic factors affecting glacier area variability

Increase in glacier mass in this geographical region is mainly due to snowfall accumulation. Mass loss (ablation) occurs mainly by melting, and the consequent runoff, and also partially by sublimation (MacDonell et al., 2013). In order to evaluate the contribution of snowfall on these glaciers, we analyzed the measurements of snow water equivalent (SWE) from stations located in the vicinity of each glacier (see Fig. 1). The mean annual cycle of the SWE for each station for the period 1990–2013 is shown in Fig. 5. Notice that on average snowfall episodes start in May, but early snow can occur in late April. Furthermore, the figure shows that the seasonal melting starts in September in station Toscas, and in October, in Laguna Diamante. The annual cycle of snow accumulation at these stations, confirms that the end of the ablation season occurs between the end of March and the beginning of April, prior to the snowfall period. Therefore, satellite images taken in late March-early April, as selected for this study, allow the observation of glacier extent without potential interference from seasonal snow. Larger values of accumulated snow are observed at station Laguna Diamante, situated approximately 120 km south of station Toscas, and it is also obvious that melting starts later. This is consistent with the fact that there is a gradient of precipitation towards the south in the region due to the passage of frontal systems and that higher temperatures may be found to the north, even though both stations are located at similar altitudes.

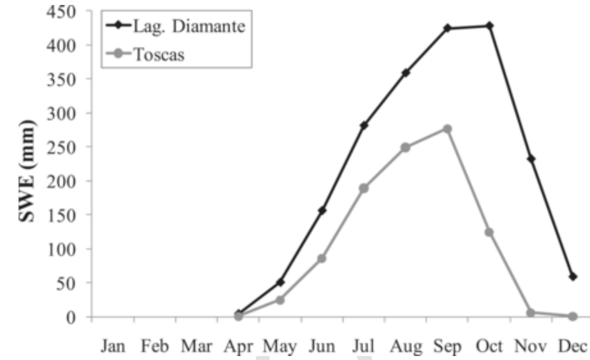

Fig. 5. Mean annual cycle (1990–2013) of Snow Water Equivalent for stations Toscas (33.16°S, 69.89°W, 3000 m) (grey) and Laguna Diamante (34.2°S, 69.7°W, 3250 m) (black). (SWE data obtained from Subsecreatría de Recursos Hídricos de la Nación, Argentina).

The time series of annual maximum SWE in each station provides insight into the interannual variability of snowfall. Note that both series in Fig. 6 show large interannual variability, from almost no snow accumulation in some years (1998, 2004 and 2010), up to values of 1000 mm SWE in other years. In this figure, El Niño and La Niña events in winter are marked with red and blue, respectively. In most of the cases, the influence of ENSO events is evident simultaneously but it is important to note that the starting month of the ENSO event will determine the strength of the influence on the accumulated snow over the Subtropical Central Andes. Station Laguna Diamante shows a linear trend of −10.5 mm/year over the total period, which resulted significant at the 95% level of significance. On the other hand, station Toscas presented a slight increase of 1.4 mm/year, although non-significant. There is also a very different behavior in these time series between 1991 and 1994. In summary, the SWE from stations close to each of the glaciers present opposite behavior, but rather surprisingly, not in the direction that would explain the evolution of the glacier area in their vicinity.

Table 3 presents temperature trends for the closest point of CRU to the SWE stations, Toscas and Laguna Diamante. Near Toscas, there is a significant warming in austral summer and spring. Near Laguna Diamante trends are also positive in these seasons but not significant. In autumn, there is a non-significant warming in the latter and Toscas shows virtually no change. In winter, there is also no change in Toscas while a negative non-significant trend is evident in Laguna Diamante.

Table 4 shows the seasonal means and trends of the height of the 0 °C isotherm for station Santo Domingo for the period 1989–2015. Mean values of this variable are below 3000 m in winter, while the

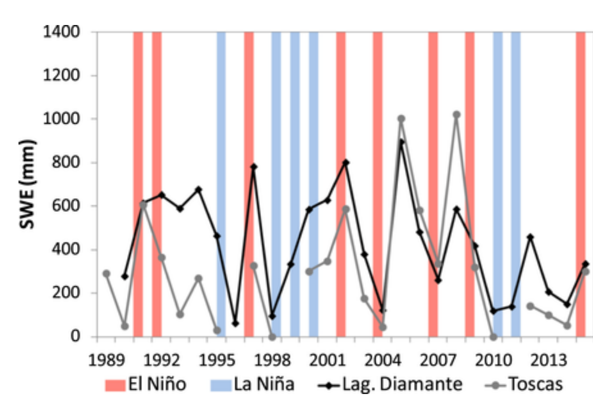

Fig. 6. Annual maximum of Snow Water Equivalent from stations Toscas and Laguna Diamante in the period 1989–2015. Station Laguna Diamante starts in 1990 and station Toscas is missing data from 3 years in this period (1996, 1999 and 2011). Color bars indicate the phase of the ENSO in each winter: red for El Niño and blue for La Niña. The absence of bar indicates a neutral state.

Table 3
Temperature trends (°C/decade) for Climate Research Unit (CRU) time series of the nearest points to Toscas and Laguna Diamante for the period 1989–2014. Values shown in bold are significant at the 95% level of confidence.

	Toscas	Laguna diamante
DJF	**0.27**	0.22
MAM	0.20	0.06
JJA	0.03	−0.15
SON	**0.39**	0.26

Table 4
Seasonal mean (m) and trend (m/decade) of the height of the 0° isotherm for the period 1989–2015 from the radiosonde station Santo Domingo.

	Mean	**Trend**
DJF	4237.8	3.9
MAM	3824.6	4.0
JJA	2992.4	−12.7
SON	3369.4	−56.8

highest elevations are found in summer, above 4000 m. Seasonal trends were not significant at the 95% level of confidence, but it can be seen that in summer and autumn small increases occurred, while in winter and spring, negative trends are found.

4. Discussion and conclusions

In the present study we analyzed the evolution of two glaciers in the Subtropical Central Andes region in the period 1989–2015. This semi-arid region is home to large populations on both sides of the Andes that depend on water from the mountains for their livelihoods. Particularly vulnerable are agricultural activities such as vineyards –sometimes located at high altitude- that depend on Andean water for irrigation, both in central Chile and in the province of Mendoza in Argentina. The main source of yearly runoff is the seasonal snowpack melt and, to a lesser extent, glacier melt. The latter becomes more important in dry years, when snow can be scarce during the cold season.

We selected two glaciers that are located in the province of Mendoza, Argentina, only 130 km apart, and present similarities in their height and orientation, but with different environmental conditions. The first glacier selected, Alto de Plomo, is a valley glacier located close to the main highway connecting Argentina and Chile. The second glacier evaluated, Volcán Maipo, is a mountain glacier and is located further south within a protected nature reserve.

A new tool was developed to automatically delineate the outline of areas covered by snow or ice, using the latest available sensor from the Landsat satellite: OLI-TIRS. We have proposed a ratio between bands 5 and 6 of OLI-TIRS to delimit the glaciated areas, similar to the widely used band ratio TM and ETM 4 and 5, at several sites around the world by different authors. We found a suitable threshold to distinguish snow and ice surfaces that facilitates the use of a consistent methodology for two Landsat scenes, and that can be used in other scenes from sensor OLI-TIRS in other regions. Using the thresholds for the band ratios, we have applied it to determine the outline of Alto del Plomo and Volcán Maipo glaciers from images obtained during several years in the period 1989–2015.

The results of the time evolution of the areal extent determined from this technique indicate that both glaciers have experienced advances and retreats during these 27-years period. Only the Alto del Plomo glacier showed a clear retreating trend during the entire period, with a total area loss of 3.4 ± 0.3 km^2 (~18% areal loss). This glacier presents a retreat rate of −0.08 km^2 per year, similar to reported retreat rates in others parts of the world, such as the ice cap on Kilimanjaro in East Africa (Thompson et al., 2009) (~−0.07 $km^2\ yr^{-1}$), on Ellesmere Island in the Canadian Arctic (Braun et al., 2004) (~−0.05 $km^2\ yr^{-1}$) and Mount Agrı Ice Cap in Turkey (Sarikaya, 2012) (−0.07 $km^2\ yr^{-1}$). It is also consistent with the reduction rate of the glaciers from the Aconcagua river basin at similar latitude, on Chilean territory (Bown et al., 2008) (−0.06 $km^2\ yr^{-1}$). Mass loss is also evident in the terminal front of Alto del Plomo and at high elevation in its accumulation area. This behavior is consistent with the findings from Malmros et al. (2016), that found widespread glacier shrinkages of 30 ± 3% from 1955 to 2013/14 in the sector between 32°9′ and 33°4′S, that includes the location of Alto del Plomo glacier. In contrast, results of the time evolution of the areal extent of the Volcán Maipo glacier showed much less variability, with a net change of −0.19 ± 0.02 km^2 (~4.3% areal loss) during the entire period. These results are rather dramatic (18% versus 4.3% areal loss) and represent very different behavior for these two glaciers that are located in the same general geographic region and at a similar altitude. In order to understand such different behavior in glaciers located in the same region and at the same altitude, we discuss now the factors that affect glacier mass balance: temperature and precipitation.

Surface temperature and the elevation of the 0 °C isotherm are two important factors in the modulation of the evolution of glaciers. Several authors have highlighted the scarce availability of meteorological stations in the region, especially at high elevation, which hampers the possibility of carrying out climatic studies (e.g. Viale and Nuñez, 2011; Rusticucci et al., 2014). Falvey and Garreaud (2009) analyzed temperature trends in the period 1979–2006 for selected surface stations in central Chile, west of the Andes and also in Argentina to the east of the Andes, and found an increase in surface temperature over central Chile, the Andes and in the province of Mendoza. Rusticucci et al. (2014) analyzed surface winter temperature trends in the southern Central Andes region through gridded datasets and reanalysis, and found a significant warming in the period 1979–2010 between 32° and 35°S. In this work, we selected the nearest points of CRU gridded datasets to the selected glaciers in order to explore seasonal surface temperature trends in the period 1989–2014. We found a significant warming trend in spring and summer, when seasonal melting occurs, only near station Toscas. The results of Rusticucci et al. (2014) and the trends presented here indicating surface warming can partially explain the decrease observed in the Alto del Plomo total glaciated area. Furthermore, we did not find a significant trend in the altitude of the 0 °C isotherm from the Santo Domingo (Chile) radiosonde station, consistent with the results presented in Rusticucci et al. (2014) for this variable in winter over the period 1979–2010.

The main mass contribution to mountain glaciers is precipitation, especially in the form of snowfall. The time series of SWE from stations in the vicinity of each glacier show large interannual variability, even years with almost no accumulation, which can be crucial for water availability in this transitional, semi-arid region. The Toscas station, close to Alto del Plomo glacier, shows a slight but non-significant increase in SWE (1.4 mm/year) not quite consistent with the large areal decrease (~18%) observed in the 27-yeard period. In contrast, the significant negative trend found in the station Laguna Diamante (−10.5 mm/year) does not quite correspond to the long-term behavior of Volcán Maipo glacier, that exhibits only 4.3% areal loss.

Given that the difference in the observed recent evolution of glaciers cannot be entirely explained by the meteorological variables presented here, we hypothesize here that the environmental conditions that surround them, specifically, the presence of aerosol particles might be key factor in determining the different behavior of these two glaciers. As mentioned, Alto del Plomo glacier is located near the main highway that connects Argentina and Chile. Approximately 770 diesel-fueled trucks per day on average (APROCAM, 2017) cross the border at around 3000 masl and their emissions constitute a source of particles at high elevation that may deposit over snowpack and glaciers. Moreover, widespread mining activities are present at high elevation in this area and the large off-road vehicles also make use of diesel fuel. Dust deposition may occur over the glacier surface affecting the energy balance through changes in the surface albedo. Even though these sources may be small, their emissions at high elevation make them more likely to have a relatively large impact on the nearby cryosphere (Molina et al., 2015). Malmros et al. (2016) has found different climate sensitivities from glaciers in the Chilean side near our study area, and proposed that deposition of mining related dust particles on the glaciers' surface could influence surface energy balances. Oerlemans et al. (2009) also evidence this phenomenon affecting glaciers in the Alps. In contrast, the Volcán Maipo glacier is located in a nature reserve area away from local sources of traffic emissions and mining activities, where dust deposition would be less likely to occur.

The hypothesis proposed here, that the impact of dust deposits over the glaciers may lead to local accelerated melting, needs to be tested with studies that evaluate other factors in the evolution of the areal extent of these glaciers. Regardless, we highlight the relevance of conservation policies of the cryosphere because of their relevance in the hydrological cycle of the surrounding areas.

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