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Recent glacier variations on Mount Melimoyu (44°50′S-72°51′W), Chilean Patagonia, using Sentinel-2 data

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ABSTRACT

This work analyzed the application of Sentinel-2 multispectral imagery and GLIMS data for mapping glacier retreat and to estimate glacier area changes of Mount Melimoyu, located in northern Patagonia, Chile for the period between 1970 and 2017. The results showed a decrease of about 35.61% in the area for the period analyzed and there is a continuing retreating trend in the region. The decreasing trend in mean annual precipitation may explain the recent glacier changes, which indicates a large sensibility for meteorological variability of glaciers, which is influenced by geomorphometry and glacier area, in the region. Using Sentinel 2 imagery, we provided inventory of rock glaciers in the study area. Glacier outlines obtained through manual delineation showed comparable results with the glacier outlines using Sentinel-2 MSI data in the study area, which shows greater accuracy in glacier mapping using Sentinel-2 data.

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Glacier Retreat; Geomorphometry; Remote Sensing; Chilean Patagonia; Sentinel-2

1. Introduction

Monitoring the changes in glacier surface is essential for understanding glacier dynamics and glacial geomorphological changes (Hubbard et al. 1998). Rivera et al. (2006) showed that glacierized areas of volcanoes in Patagonia are shrinking due to changes in the regional climate. Other than regional and global climate changes, volcanic activities (Rivera et al. 2012) and anthropogenic factors, such as mining activities (Urkidi 2010), are creating threats to glaciers in the central Andes of Chile. In the Chilean and the Argentinean Andes, glaciers have shown a negative mass balance (Coudrain et al. 2005; Francou et al. 2003; Casassa et al. 2007; IPCC 2013). Davies and Glasser (2012)

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mentioned that there was an accelerated shrinkage of glaciers in the Patagonian Andes since the 1980s and also that a few isolated glaciers and ice caps shrank faster between 1986 and 2001 compared to the 2001–2011 period. Similar observations were done by Paul and Mölg (2014) regarding glacier surface changes and also a 59% increase in the area of glacial lakes between 1985 and 2011. Furthermore, Pellicciotti et al. (2014) pointed out that Patagonian glaciers were shrinking and thinning in the past decades and similar results were presented in Rignot et al. (2003) and Rivera et al. (2007). Mernild et al. (2015) mentioned that the mass loss in this region is $-295 \pm 195\,\text{kg m}^{-2}\,\text{yr}^{-1}$ for the 2003–2012 periods. Malmros et al. (2016) demonstrated an area loss of 16% in the central Chilean Andes from 1989 to 2013/14.

Despite the fact that the ice-covered regions in the Chilean Andes are eventually decreasing in size due to regional and global factors, a number of studies on mass balance fluctuations and glacier-climate interactions were supported by mining companies (Rabatel et al. 2011; MacDonell et al. 2013; Cornwell et al. 2016). As mentioned by Pellicciotti et al. (2014), even though the glaciers in the Andes of Chile are shrinking and loosing mass, the number of studies conducted and the available data are still insufficient to provide a synopsis of glacier changes in the past and to explain the causes of the observed glacier changes.

Multitemporal remote sensing data is a key element for the accurate mapping of glacier fluctuations, which is one of the key indicators of climate change (Williams et al. 1991; Hall et al. 2003). Digital elevation models (DEM) and other remote sensing data can be used for the interpretation and characterization of glacial environments (Rignot et al. 2003). Kääb et al. (2002) emphasized that DEMs generated by photogrammetric methods from ASTER optical sensor data have to be evaluated in terms of accuracy and applicability for glaciological studies, allowing a series of studies, such as geomorphometric analysis, including mountainous regions. This article to investigated variations in the area of glacierized surface of Mount Melimoyu (44°05′S - 72°51′W) for the period from 1970 to 2017 and the relationship between the geomorphometric distribution of glacier surface and their temporal sensitivity using ASTER-GDEM v.2 and Sentinel 2 data.

2. Study site and climate conditions

Mount Melimoyu (Figure 1) is a permanently ice-covered active stratovolcano (2400 m a.s.l.) with a length of 10 km in the east-west direction (Lliboutry 1956; Naranjo and Stern 2004) and a 1.5 km diameter summit crater, which has a total of 16 glaciers radiating out in all directions. This poorly studied ice-covered volcano without historical eruptive activities is located in the southern volcanic zone in the southern Andes region (northern area of Chilean Patagonia). The study area is situated in the XIth administrative region of central Chile in the Aisén region. This region is characterized by a complex landscape with many fiords and lakes formed by glacial laminar erosion of the Patagonian ice sheet during the Quaternary. The study area is located in the South of the glaciological zones of Chile, determined by the National Glacier Strategy (DGA) in 2009.

The studied area has a cold climate with oceanic influence on heavy rains, strong westerly winds and high humidity due to the existence of the Andean orographic barrier (Garreaud et al. 2009). According to Koppen (1918), the western sector of the Andean reliefs in Aysen Region, where the Mount Melimoyu is located, has humid temperate climate with short and cold summer without dry season and pronounced maritime influence. The Patagonian glaciers are influenced by mid-latitude atmospheric circulation pattern and Antarctic cold fronts (Rasmussen et al. 2007). Synoptic-scale winds are

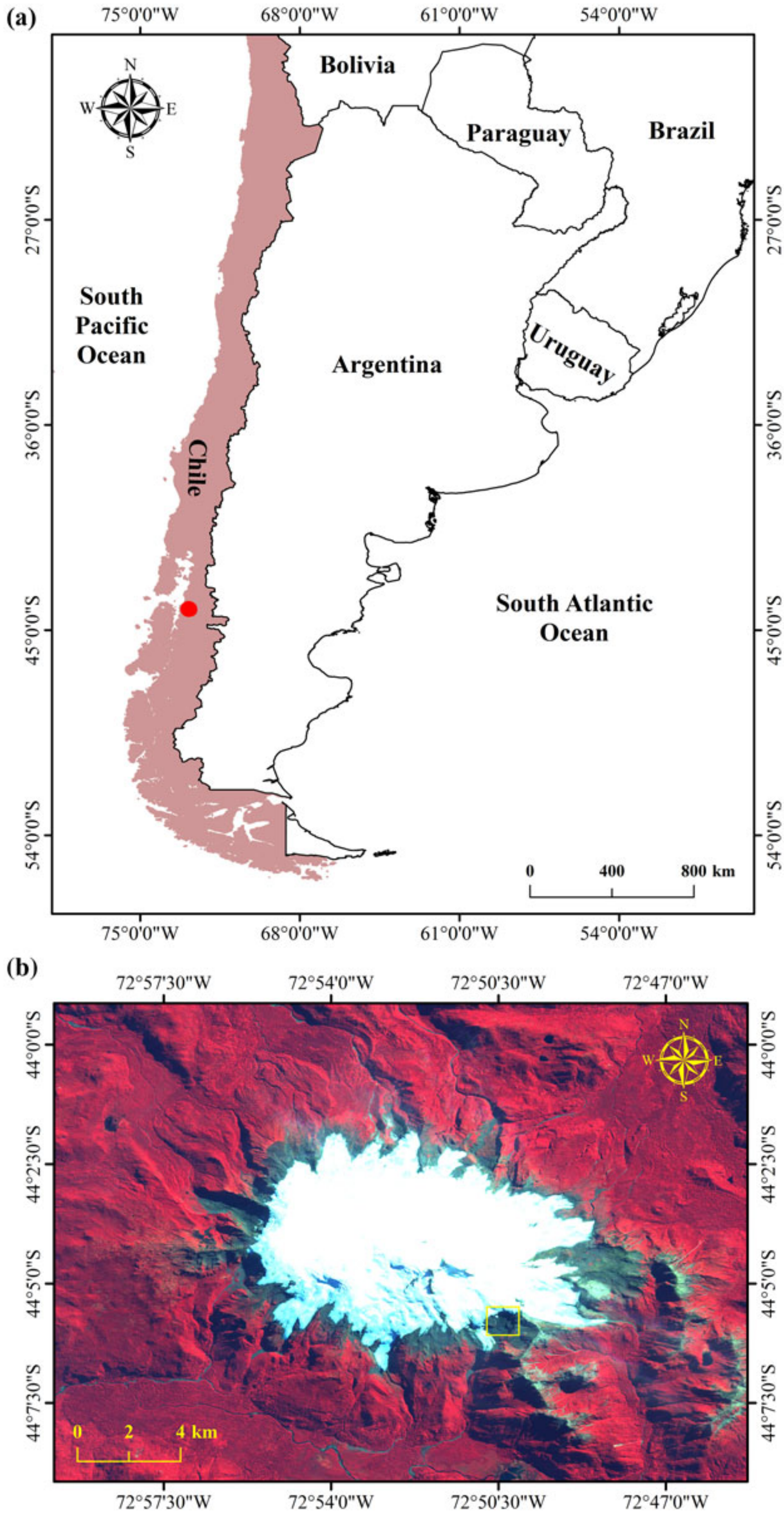

Figure 1. (top) Geographical location of Mount Melimoyu in Central Chile area; (bottom) Sentinel-2 image subset acquired in 2017 with RGB (8-4-3) false-colour composite. Rock glacier identified is shown within yellow block.

predominantly westerly (Kalthoff et al. 2002), from the Pacific Ocean, and steep Andean relief generate a high amount of precipitation in the Patagonian Ice Field (Rivera and Casassa 2004). The orographic effect on the Patagonian circulation is high, with the precipitation may reaches up to 5,000 mm/year westward and to 200 mm/year eastward (Casassa et al. 1998). The mean precipitation for the period 1970–2015 in this region is 2213 mm, with a maximum and a minimum of 3015 and 1405 mm, respectively (recorded by La Junta weather station, 45 m a.s.l., at Lat: 43°58′S; Long: 72°25′W).

According to the temperature data near the study area (Chaitén Lat: 42°56′S; Long: 72°42′W and Puerto Aisén Lat: 45°24′S; Long: 72°44′W), the average annual surface air temperatures is between 9 and 9.5 °C. The variations in temperature values are minima along the coastal sector and increase upward in the continent. The lack or discontinuity of records prevents us analyzing the trends in climatological data for long periods. However, Rosenbluth et al. (1997) and Falvey and Garreaud (2009) indicated an increase of ∼0.25 °C per decade in the air temperature for the central Andes between 1975 and 2001.

3. Data

For updating the variations in glacier area between 2000 and 2017, Sentinel 2 (level 1C) data were used (Table 1). Sentinel 2 is a large-scale, high-resolution, multi-spectral European mission (Sentinel - ESA). Level 1C includes radiometric and geometric corrections, orthorectification, and spatial resolution of up to 10 m.

The Sentinel-2 data were generated by the European Space Agency (ESA) and its system is based on the concurrent operations of two identical satellites flying on a single orbit plane but phased at 180° each, hosting a Multi-Spectral Instrument (MSI) covering the visible to the shortwave infrared spectral range and delivering high spatial resolution imagery at global scale with a high revisit frequency (of 5–10 days). The MSI aims at measuring the reflected radiance from the earth surface through the atmosphere in 13 spectral bands spanning from the Visible and Near Infra-Red (VNIR) to the Short Wave Infra-Red (SWIR). The potential use of Sentinel-2 data for glacier mapping has been discussed in two latest review papers (Kääb et al. 2016; Paul et al. 2016). Recently, Sentinel-2 data have been used extensively in the Andes for glacier mapping (e.g. Veettil 2018; Veettil et al. 2018; Idalino et al. 2018).

For the comparative analysis of glacier retreat, we used the GLIMS (Global Land Ice Measurements from Space) data (Table 1) and processed in ArcGIS® software package. The Randolph Glacier Inventory (RGI 6.0) is a global inventory of glacier outlines (RGI

Table 1. Remote sensing data used in this study.

Data	Scale/spatial resolution	Period	Source
Sentinel 2 - L1C T18GXS_A00959	10m	2017/March/17	USGS
ASTER-GDEM v.2 Entity ID: ASTGDEMV2_0S45W073	30m (spatial) and 2.4 arc-sec. (horizontal acuracy) Aprox. 12 m (vertical error) Tachikawa et al. (2011)	2011/October/17	USGS
Shapes of the glaciers	30m	1970/January/01 1986/January/14 2000/June/15	GLIMS - https://www.glims.org/RGI/

Consortium 2017), which is a supplementary data to GLIMS. Production of the RGI was motivated by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5).

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) was developed jointly by the U.S. National Aeronautics and Space Administration (NASA) and Japan's Ministry of Economy, Trade, and Industry (METI). It covers the earth surface between 83°N and 83°S and is comprised of 22,702 tiles. Tiles that contain at least 0.01% land area are available for studies in the Geographic Tagged Image File Format (GeoTIFF) format. Geomorphometric data was obtained using ASTER-GDEM v.2 data (Table 1).

The La Junta weather station (located at 35 km northeast of Mount Melimoyu) has provided the precipitation data used in this study. Meteorological data from Aysén-Ad station (located at 147 km southeast of Mount Melimoyu) were also used when precipitation data from La Junta station is absent for some years. The *Pearson* (r) test for data from these two stations show a correlation of 0.35 for average precipitation. The Aysén-Ad station (located 147 km southeast of Mount Melimoyu) has provided the temperature data used in this study. Meteorological data from Chaitén-Ad station (located 127 km north of Mount Melimoyu) were also used as temperature data from Aysén-Ad station is absent in some years. The *Pearson* (r) test for data from these two stations show a correlation of 0.32 for annual average temperature. These data are available from *Dirección General de Aguas* (DGA), Chile (www.dga.cl).

4. Methodology

The geomorphometric characterization of the study area was performed by generating and interpreting slope maps, hypsometry and aspect using ASTER-GDEM v.2 data. Prior to glacier surface change analysis, all satellite data were coregistered to the 2017 Sentinel-2 scene and GLIMS data. An extraction of total glacier areas and outline delineation were performed for the quantification of glacial area loss as well as retreat rates for the period between 1970 and 2017. Glacier boundaries for 1970, 1986 and 2000 were provided by the GLIMS. In order to get 2017 glacial outline (scale 1:5.000), Sentinel-2 data with false-colour composite (R-G-B: 8-4-3) obtained on 03/17/2017 were used.

A ± 1 pixel uncertainty has been assumed for glacier areas more than 0.1 km^2 (Frey et al. 2012), which is applied in many recent studies. This uncertainty was estimated based on the Equation (1):

$$A_{er} = \pm 100\ (f_s \cdot n \cdot m)/A_{gl} \tag{1}$$

Where, A_{er} = uncertainty associated with glacier area, A_{gl} = glacier area from the satellite image, n = number of pixels defining the perimeter of a glacier, m = spatial resolution of Sentinel-2 image expressed as area of a pixel (100 m^2 for a Sentinel-2 image with 10 m pixel size), and f_s is the systematic fractional pixel error and was taken as 1. An additional uncertainty of ±0.7% was added based on comparing the Sentinel-derived area with Google Earth-derived glacier polygon. The total uncertainty was estimated as the root sum square of ±1 pixel uncertainty and additional ±0.7% uncertainty as given in Bolch et al. (2010).

We analyzed the differences between topographic and geomorphometric characteristics of each glacier on Mount Melimoyu. Attributes such as glacier area and its variation over time were also evaluated in comparison to the characteristics determined for each glacier. The evaluation of glacier maps and the analysis of the data resulted from the comparative analysis among glaciers, observing the differences in sensitivity to the regional atmosphere warming trends have been done for each glacier.

5. Results

5.1. Overall glacier surface changes

The glacierized area of Mount Melimoyu has been estimated as 52.14 km^2 in 2017 using Sentinel-2 data. The Figure 2 and Table 2 show the total glacier surface loss from Mount Melimoyu for the period between 1970 and 2017 as 28.83 km^2, which represents 35.6% (0.61 km^2/year) of the total glacier surface in 1970 (80.97 km^2). The period of highest glacier surface loss has been observed as between 1970 and 1986 with 23.04% (1.33 km^2/year) loss from its initial area in 1970. The retreat of glaciers 6, 10, 13 and 16 was more pronounced between 1970 and 1986 as well as between 2000 and 2017. Glaciers 1, 3, 7, 8,

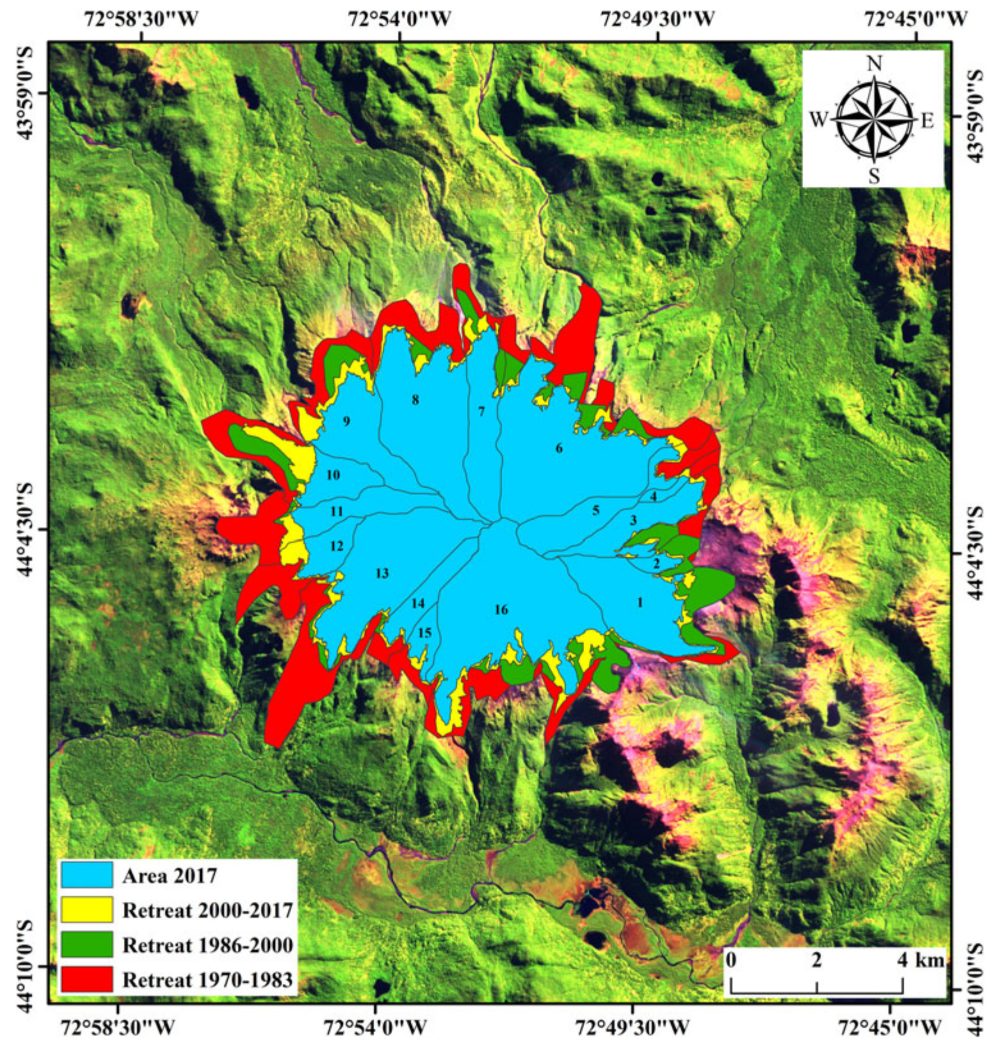

Figure 2. Glacier shrinkage map for Mount Melimoyu (1970–2017).

Table 2. Glaciers area changes and comparison of glacier retreat rates (1970–2017).

Glacier	Area (km^2) 1970	Area (km^2) 1986	Area (km^2) 2000	Area (km^2) 2017	Surface change rate (km^2/year) 1970–1986	Surface change rate (km^2/year) 1986–2000	Surface change rate (km^2/year) 2000–2017	Total Surface change (km^2) 1970–2017	Total Retreat rate (km^2/year) 1970–2017
1	6.07	5.78	4.48	4.1	−0.02	−0.093	−0.022	−1.97	0.042
2	0.5	0.92	0.42	0.36	0.026	−0.036	−0.0035	−0.14	0.003
3	3.63	2.74	2.43	2.21	−0.055	−0.022	−0.0129	−1.42	0.03
4	0.54	0.28	0.31	0.27	−0.016	0.002	−0.0023	−0.27	0.006
5	2.89	2.35	2.44	2.32	−0.034	0.006	−0.007	−0.57	0.012
6	13.12	9.8	8.84	8.28	−0.21	−0.068	−0.0329	−4.84	0.103
7	4.02	3.57	3.29	3	−0.028	−0.02	−0.017	−1.02	0.022
8	8.35	6.75	6.76	6.43	−.1	0.0007	−0.0194	−1.93	0.041
9	4.95	4.03	3.81	3.08	−0.06	−0.016	−0.0429	−1.87	0.039
10	4.25	2.97	2.32	1.48	−0.08	−0.046	−0.0488	−2.76	0.059
11	3.73	2.18	2.13	1.87	−0.097	−0.0028	−0.0153	−1.86	0.039
12	2.62	1.21	1.45	1.11	−0.088	0.017	−0.02	−1.51	0.032
13	9.45	6.59	6.6	6.21	−0.18	0.0007	−0.0229	−3.24	0.069
14	2.02	1.51	1.54	1.45	−0.032	0.0021	−0.0053	−0.57	0.012
15	1.31	0.84	0.86	0.73	−0.029	0.0007	−0.0076	−0.58	0.012
16	13.52	10.81	10.71	9.24	−0.17	−0.007	−0.0864	−4.28	0.091
Overall glacier coverage	**80.97**	**62.33**	**58.39**	**52.14**	**−1.165 (−1.44 %/year)**	**−0.28 (−0.45%/year)**	**−0.367 (−0.63 %/year)**	**−28.83 (−35.6%)**	**0.61 (0.76 %/year)**

Negative values indicate loss of glacier surface.

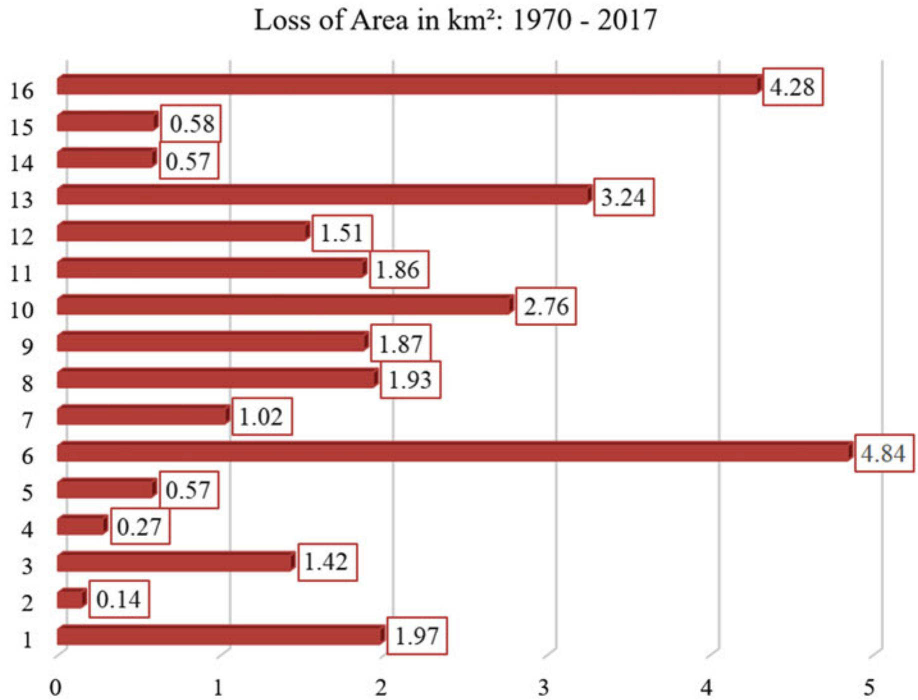

Figure 3. Surface loss (in km^2) for each outlet glacier between 1970 and 2017.

9, 11 and 12 presented a relatively average retreat and Glaciers 2, 4, 5, 14 and 15 showed smaller area loss (Figure 3).

5.2. Characterization of the glaciers on Mount Melimoyu

Through visual analysis of Sentinel-2 data, it has been observed that there are 16 glaciers radiating from Mount Melimoyu (Figure 2), shaped and characterized as mountain glaciers. The glaciers were divided based on the elevation as: lower altitude (<1,301 m), medium altitude (1,301–1,500 m) and high altitude (≥ 1,501 m). The drainage of the glacier number 16, which has the lowest elevation (670 m), present an ice flow at the terminus and formed as a rock glacier (with 0.21 km^2 of area), which has not been mapped in GLIMS (Figure 1). The estimated uncertainty for glacier area from Sentinel-2 data was around ±2.6%. Details of minimum, maximum and mean elevation of glaciers on Mount Melimoyu is presented in Table 3. The glacierized areas of Mount Melimoyu have 670 m of minimum elevation, 2,399 m of maximum elevation and mean elevation of 1,539 m. Overall glacier surface distribution per elevation zones are shown in Figure 4. Nearly 97% (0.16 km^2/year) of the glacierized areas below 800 m a.s.l. and 71% (0.28 km^2/year) between 800 and 1200 m have lost during the study period. However, there were no changes in glacier coverage occurred above 1600 m a.s.l.

Overall glacier surface distribution per different slope classes (in degrees) is shown in Figure 5. Glacierized areas with slope higher than 35° lost more than 85% (0.14 km^2/year) of its ice-covered area in 1970 during the study period. Lowest surface loss was observed in regions with slope between 7° and 21°; slightly more than 23% (0.22 km^2/year) between 1970 and 2017. Nearly 28% (0.02 km^2/year) of the ice-covered area in 1970 was lost, where slope below 7°, most of this region belong to lower altitudes.

Table 3. Minimum, mean and maximum elevation of the glaciers on Mount Melimoyu.

Glacier number	Minimum (m)	Maximum (m)	Mean (m)
1	737	2,083	1,421.5
2	1,295	1,680	1,487
3	891	2,255	1,573
4	962	1,294	1,128
5	802	2,399	1,600
6	854	2,315	1,584
7	998	2,308	1,653
8	987	2,287	1,637
9	1,168	1,967	1,567.5
10	1,387	1,797	1,592
11	1375	2,076	1,725.5
12	1,144	1,732	1,438
13	700	2,292	1,496
14	1,180	2,264	1,722
15	1,080	1,665	1,372.5
16	670	2,399	1,534.5

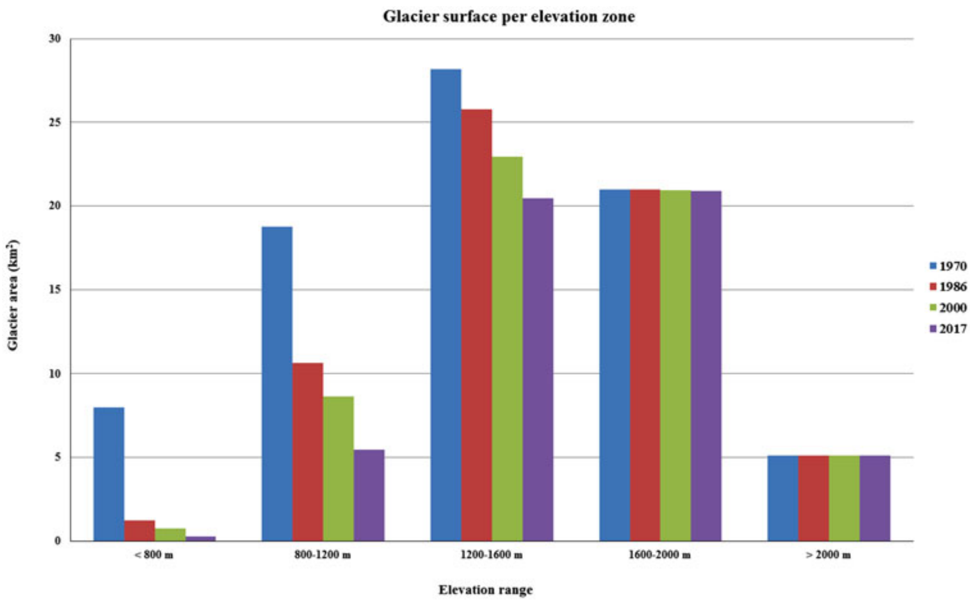

Figure 4. Glacier area distribution per elevation range on Mount Melimoyu.

Regarding the orientation, the Mount Melimoyu glaciers presented differences in flow directions (Figure 6), which is common for an ice cap covering a volcano summit. Highest shrinkage of glaciers occurred on the western (51% - 0.07 km^2/year) and north-western (50.5% - 0.09 km^2/year) slopes. Lowest shrinkage occurred on the northern (28% - 0.097 km^2/year) and southern (29.9% - 0.091 km^2/year) slopes.

5.3. Variations in precipitation and air temperature

The graph of annual average precipitations (Figure 7) shows a mean value of 2,266 mm/year. The lowest precipitation value of 719 mm/year and the highest value of 3,515 mm/year show a variation from to 2,796 mm between these values. The variation in mean

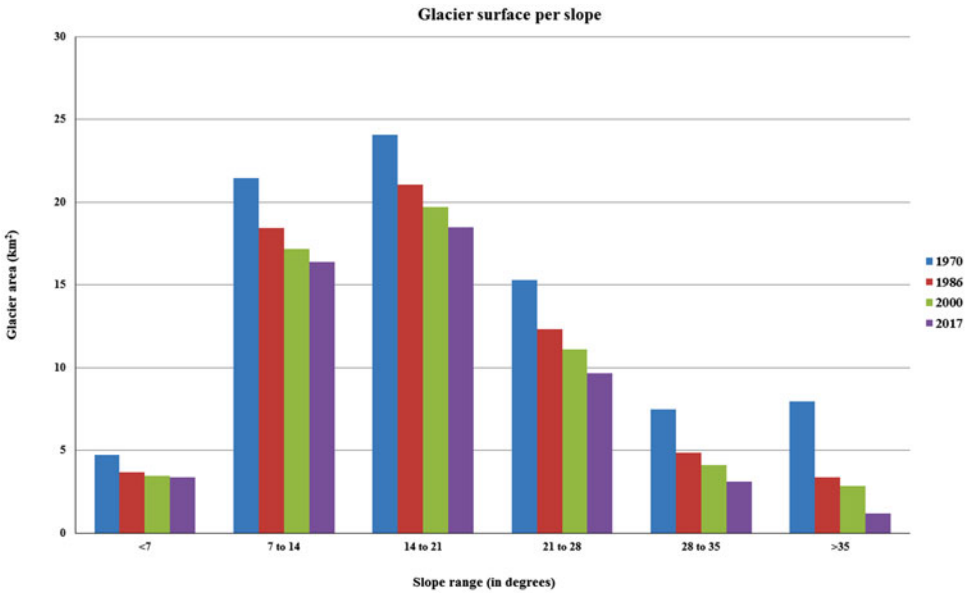

Figure 5. Glacier area distribution per slope on Mount Melimoyu.

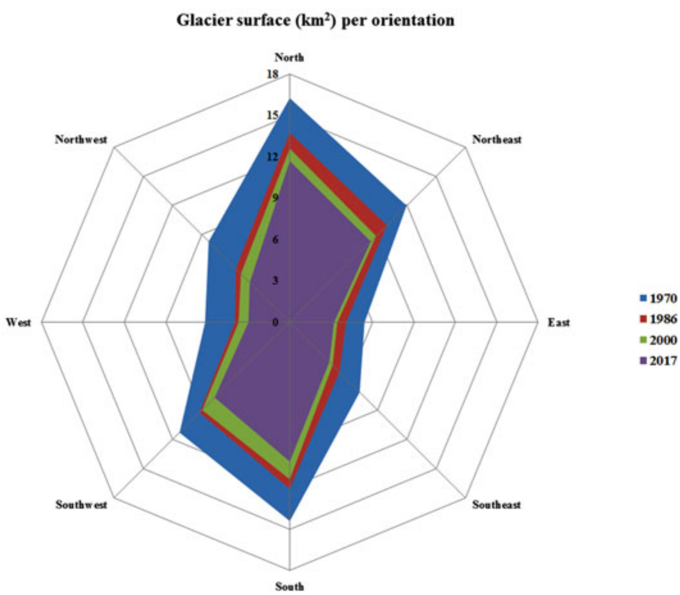

Figure 6. Glacier surface distribution per orientation on Mount Melimoyu (1970–2017).

annual was formed a linear gradient of trends represented by a dashed line. This line has an inclined conduit with trends to decrease in the analyzed period.

The graph for annual average temperatures (Figure 8) shows a mean value of 9.09 °C during the study period. The average temperature in 1970 was 8.28 °C and in 2017 it was 9.52 °C show a variation from to 1.24 °C between these values and an annual increasing of 0.025 °C in average temperature.

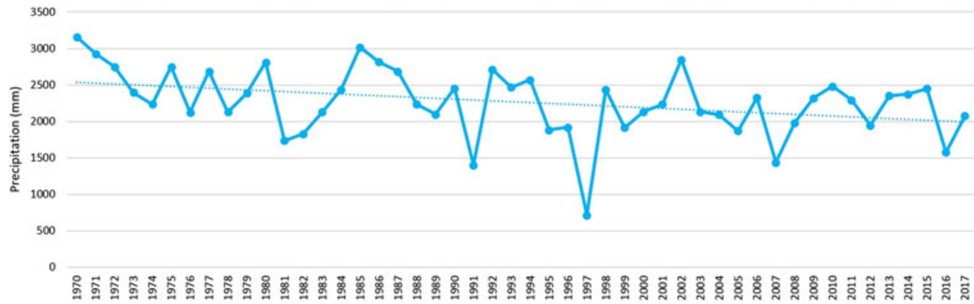

Figure 7. Trends in the average annual precipitation (1970–2017) at La Junta station, Chile.

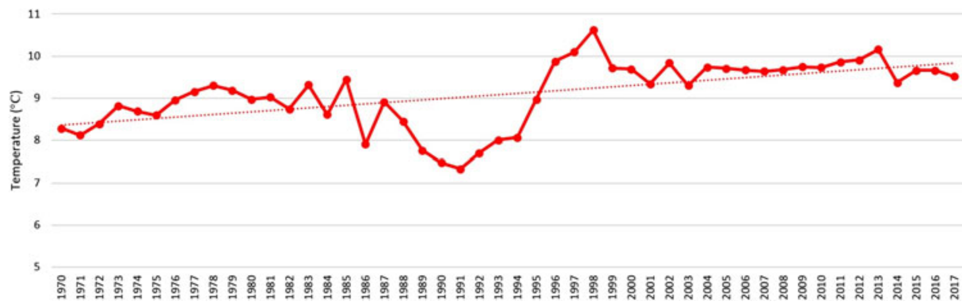

Figure 8. Trends in the annual average air temperature (1970–2017) at Aisén Ad and Chaitén Ad stations, Chile.

6. Discussion

In general, the trends in glacier retreat observed on Mount Melimoyu were similar to the results given in Pellicciotti et al. (2014). The same study (Pellicciotti et al. 2014) pointed out that the Patagonian glaciers, including those glaciers in the northern Zone, were shrinking and thinning in the last decades. Similar observations can be found in a number of studies (e.g. Rignot et al. 2003; Rivera et al. 2007; Masiokas et al. 2008; Davies and Glasser 2012; Willis et al. 2012).

In the study area, there is no evidence of historical volcanic activity or recent eruptive record, but there could be an unknown geothermal activity, even though a very little is known about the responses to climate change in these regions (Masiokas et al. 2008; Schaefer et al. 2013). Rivera et al. (2006) observed that the glaciers located on volcanoes are shrinking in response to climate forcing and this observation is affirmed in recent studies (e.g. Pellicciotti et al. 2014).

The observed trends in glacier retreat from this study for Mount Melimoyu can be related to several factors, such as decreasing precipitation, as highlighted by Masiokas et al. (2008) for the Patagonian glacier recession, principally for the period between 1912 and 2002. Mid-tropospheric warming has been highlighted as one of the causes for glacier retreat in central Chile (Carrasco et al. 2005). The decreasing trend in mean annual precipitation is not the only factor for glaciers retreating in the Chilean Southern Andes. The air temperature data showed an increasing trend in the analyzed period (0.025 °C/year). This result is in good agreement with the works of other authors in this region that show an increase of 0.25 °C/decade (Rosenbluth et al., 1997; Falvey and Garreaud, 2009 and Ferrando, 2014).

The results on fluctuations in glacier area for different periods (Figure 2) show different retreat rates for each glacier and these are related to its geomorphometric characteristics and size (Figures 4 and 5). The characterization of glacier dynamics on Mount Melimoyu is important for monitoring and understanding of how different topo-climatic and morphoclimatic differences in front elevation, aspect, slope and environmental characteristics might influence the pattern of glacier shrinkage on Mount Melimoyu.

All of the glaciers on Mount Melimoyu, in general, presented a continuous retreating trend. Some glaciers can be grouped based on similar retreating trends during similar periods and in their similarities in total area, maximum elevation and predominant ice flow orientation. Glaciers 6, 10, 13 and 16 presented a higher retreat rate and percentage surface loss for the period between 1970 and 2017 (Figures 2 and 3, Table 2). Glacier number 10, with high retreat, currently has the highest terminus elevation, lowest maximum elevation and a front sector with high slope and is relatively less extensive. It can be argued that glaciers 6, 13 and 16 presented similar retreat pattern due to high slope values, except glacier 10. However, these glaciers presented a current outline elevation (in 2017) not as high as the other glaciers and their areas are not very extensive. It is worth mentioning that surface changes for glacier 6 was previously analyzed in a pilot study (Idalino et al. 2018) and the results were similar.

The studied glaciers presented different predominance in ice flow orientation patterns (Figure 6) and the glacier retreat rates were not low for south-facing glaciers in study area, probably due to their lower maximum elevation compared to other high altitude mountains in the Andean Cordilleras. In contrast to the high topographic influence on the precipitation distribution observed in the Andes Mountains (Garreaud et al. 2009), no clear shrinkage differences were observed in the study area between the west and east sides of the Mount Melimoyu, which can be due to the low elevation of the mountain.

Glaciers 1, 3, 8, 9, 11 and 12 presented relatively slower retreats when compared to other glaciers (Figures 2 and 3). Analysis of geomorphometric parameters of glaciers 8, 9 and 12 (with emphasis on number 9 and 12) presented termini with a high elevation when compared to the rest of glaciers in the group. Glacier number 12, besides presenting a high elevation and slope, the current terminus also presented little extension (Figure 2 and Table 2). Glacier number 1 has the highest surface on the highest slope class and low surface for the current terminus (Figure 4), whilst glacier number 11 has a high slope in the frontal sector and its area is not as extensive as the rest (Figure 2 and Table 2).

The lower retreat of the 2, 4, 5, 7, 14 and 15 glaciers can be related to the high elevation values of the current outlines (Figures 2 and 3 and Table 2). With regard to this retreat pattern, glaciers 14, 15 and 4 also present high values to the current outline (minimum elevation). This retreat pattern, especially for glaciers 5, 7 and 14, can be related to high values of maximum elevation, which influence the mass and energy balance, when compared to the rest. Glacier number 4 presents low slope values that could influence the low flow velocity and consequently a slower retreat.

Rather than high retreat rates on western and north-western slopes, we could not find any relationship between the retreat pattern and the characteristics of the ice flow orientation (Figure 6) that explain their different retreat patterns. Nicholson et al. (2009) mentioned that this region is not characterized as high ridgelines, so the glaciers are not limited to south-facing lee slopes and denote that the glaciers in this region do not have classical altitude-delimited accumulation and ablation areas. Instead, wind patterns determine the spatial distribution of snow accumulation and glacier surface loss, which can be a direction for future research.

The image quality and pixel resolutions are relevant for delineating glacier outlines from satellite images. Areas covered by supraglacial debris and fresh snow were identified from multi-spectral Sentinel-2 imagery, as pointed given in Malenovský et al. (2012). The

10 m spatial resolution of Sentinel-2 images certainly improved the delineation of glacial terrain features and boundaries. Sentinel-2 can be used for further studies to evaluate the potential of this novel data for detecting supraglacial debris, snow and rock glaciers.

7. Conclusions

The results of this study evidenced a reduction in glacierized surface of Mount Melimoyu at the rate of 0.61 km^2/year for the period between 1970 and 2017. The findings improved the current knowledge of the widespread glacier decline pattern sampled from the cryosphere of the southern Andes. More than 1/3rd (0.79%/year) of the total glacier surface has been lost in just four decades in this subtropical region. The differences in the retreat pattern among the glaciers were identified and there are possible relations with characteristics of maximum and minimum elevation (outline elevation of the glaciers), slope and total area.

The decreasing trend in mean annual precipitations and the increase in mean annual temperature can be a possible reason for recent glacier surface changes. These variables, except a south-north facing orientation, have been observed to be related and can explain the differences in sensitivity of some glaciers to the variations in yearly average precipitation and average temperature recorded in the region in recent decades.

These results contribute to the Cryosphere monitoring efforts in this relatively less studied region, are available from Centro Polar e Climático (www.centropolar.com) and National Institute of Science and Technology–Cryosphere (http://www.ufrgs.br/inctcriosfera/), and can be used to update GLIMS. This work provides satisfactory results on application of Sentinel-2 MSI and ASTERGDEM 2 data in these environments, which enables the development of comparative studies in other areas for a better understanding of the dynamic glacier response to regional and global climate change.

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