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Glacier responses to recent volcanic activity in Southern Chile

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Abstract

Glaciers in Southern Chile (39–43°S) are characterized by frontal retreats and area losses in response to the ongoing climatic changes at a timescale of decades. Superimposed on these longer-term trends, volcanic activity is thought to impact glaciers in variable ways. Debris–ash covered Glaciar Pichillancahue–Turbio only retreated slightly in recent decades in spite of been located on Volcán Villarrica which has experienced increased volcanic activity since 1977. In contrast, the negative long-term Volcán Michinmahuida glacier area trend reversed shortly before the beginning of the explosive eruption of nearby Volcán Chaitén in May 2008, when Glaciar Amarillo advanced and a lahar type of mudflow was observed. This advancing process is analysed in connection to the nearby eruption, producing albedo changes at Michinmahuida glaciers, as well as a possible enhanced basal melting from higher geothermal flux. Deconvolution of glacier responses due to these processes is difficult and probably not possible with available data. Much more work and data are required to determine the causes of present glacier behaviour.

Keywords: glacier volcanoes interactions

1. Introduction

Ice-capped active volcanoes of Southern Chile have experienced large retreat and shrinkage in historical times (Rivera *et al* 2005). This process has been well documented as a primary consequence of ongoing climatic changes (Carrasco *et al* 2008). Volcanic activity, however, is also affecting glaciers, by a combination of factors such as destruction of glacier areas during eruptions, increasing geothermal temperature at the glacier base inducing higher basal sliding, and ash deposition on top of the glacier modifying surface albedo. Salamantin *et al* (2000) indicated that in glaciers on top of volcanoes, 25% of the mass loss can be explained by the geothermal activity. The albedo effect has already been described for Volcán Villarrica (table 1) in Rivera *et al* (2008), where highest melting rates are observed downwind from the volcanic crater due to deposition of tephra fallout. However, depending on the ash thermal conductivity and thicknesses, it is possible that these layers could have enhanced snow and ice

melting at the first stages of an eruption, but when a sufficient (though unknown) thickness threshold was reached, the layer would have reduced surface melting by insulating the snow and ice from solar radiation (Brook *et al* 2011). This kind of measurement was performed at Volcán Villarrica where it was shown that a very thin ash layer (less than 1 cm) could insulate the ice (Brock *et al* 2007). Another possible influence of the volcanic activity is the almost total destruction of the ice, for example within the caldera of Volcán Hudson (45°51'S, 72°55'W, 1905 m above sea level (m asl)) which in 1971 and 1991 experienced some of the most explosive eruptions recorded in Chile (González-Ferrán 1995).

This study includes (table 1, figure 1) the analysis of Volcán Villarrica, one of the two most active volcanoes in the Andes and largely covered by a glacier (Clavero and Moreno 2004); and Volcán Michinmahuida, an ice covered stratovolcano that last erupted 170 years ago but is located near Volcán Chaitén (42°50'S, 72°39'W, 1122 m asl), an ice-free caldera and dome which has experienced a

Table 1. Study areas.

Mountain		Volcán Villarrica	Monte Tronador	Monte Inexplorado		Vn. Michinmahuida			
Type		Active Stratovolcano	Non-active Stratovolcano	Non-active Mountain		Active Stratovolcano			
Glacier name		Pichillancahue-Turbio	Casa Pangué	Inexplorado II	Inexplorado III	Rayas	Reñihue	Turbio Chico	Amarillo
Latitude (S)		39°27'	41°08'	41°57'	42°00'	42°48'	42°47'	42°50'	42°50'
Longitude (W)		71°54'	71°52'	72°12'	72°12'	72°30'	72°25'	72°25'	72°27'
Length (km) year 2011		5.6	5.7	4.5	6.1	5.1	6.2	5.2	7.3
Area (km ²) year 2011		16.2	11.6	13.5	12.5	10.9	10.3	14.6	12.3
Elevation year 2011 (m asl)	Minimum	1725	615	1080	960	950	600	650	550
	Maximum	2825	3425	2280	2280	2450	2450	2350	2450
Frontal rate change (m yr ⁻¹)	Total 1961–2011	−24.5	−37.12	−125.0	−74.0	−30.6	−23.0	−15.5	−53.2
Area change rate (km ² yr ⁻¹)	Total 1961–2011	−0.042	−0.026	−0.13		−0.11			

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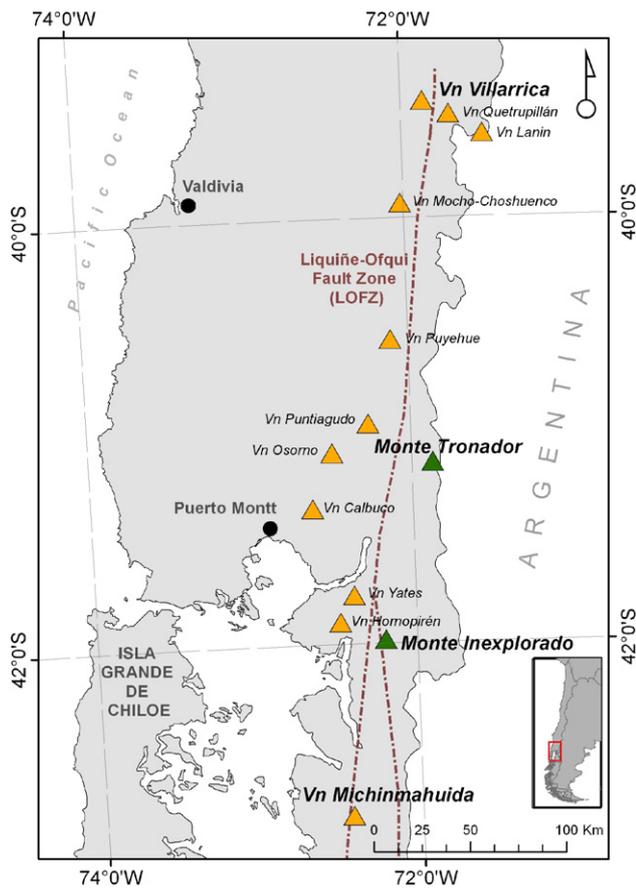


Figure 1. Location map of glacier areas located on active volcanoes (orange triangles) at the southern volcanic zone (SVZ). Also are shown are two glacier areas at non-active volcanoes included in this study (green triangles). The brown line represents the Liquiñe–Ofqui fault zone (LOFZ).

sub-plinian eruption since May 2008 (Lara 2009). Also, two non-active volcanic glaciated mountains were included in the analysis for comparison purposes.

2. Regional context

The volcanoes analysed in this work are located in the southern volcanic zone (SVZ) of the Chilean Andes, which comprises approximately sixty active volcanoes with well-known historical eruption records (Stern 2004). The SVZ is tectonically controlled by the convergence and subduction of the South American plate under the Nazca plate. The volcanoes are aligned for over 1000 km along the north–south oriented (figure 1) Liquiñe–Ofqui fault zone (LOFZ), which controls the location of most volcanoes in Southern Chile as well as those of numerous monogenetic cones (Cembrano *et al* 2000). During recent decades, several volcanoes within the region displayed explosive eruptive activity (Volcanic Eruption Indices (VEI) 1 to 3, Mason *et al* 2004), with permanent degassing, and material ejection and subsequent deposition over ice surfaces (Simkin and Siebert 1994).

The study area is within the mid-latitude climatic belt located between the Mediterranean temperate regime of

central Chile and the region under semi-permanent presence of the Westerlies (Rütlant and Fuenzalida 1991). This mid-latitude belt is characterized by dry and warm summers and wet winters with maximum precipitations of several hundreds of millimetres per year in the northern boundary of the region to a few thousands of millimetres per year in its southern part (Carrasco *et al* 2008). Unfortunately most of the regional stations are located at low altitude therefore very little is known about high-altitude precipitation and temperature changes, which have been analysed using radiosonde data (Falvey and Garreaud 2009).

Near-surface air temperatures in the study area showed a cooling trend between 1960 and 1970 at Temuco (38.5°S) and Puerto Montt (Rosenblüth *et al* 1997); however, no noticeable temperature trends were obtained between 1979 and 2006 (Falvey and Garreaud 2009). The upper atmosphere (radiosonde data from Puerto Montt at 41°S, measured between 1500 and 9000 m asl) indicates tropospheric warming of 0.12 °C/decade between 1958 and 2006 (Bown and Rivera 2007, Carrasco *et al* 2008). Because the glacierized summits are well within this upper atmospheric zone, the latter trend is what is expected to control ablation of glaciers on these volcanoes below the equilibrium line altitude (ELA) ranging from 2800 m asl at 36°S down to near 1600 m asl at 43°S (Carrasco *et al* 2005). However, the surface temperature trends may influence the sources of atmospheric moisture and thus, precipitation. Hence, the way in which regional climate may affect the volcanoes’ ice caps is a complex matter. High-altitude warming would suggest that the icecaps should be shrinking, but the controlling factor could be any changes, positive or negative, in precipitation.

The precipitation between 36° and 46°S Lat has shown a general decreasing trend in the period from 1900 to 2000, with particularly lower rainfall amounts occurring between 1970 and 2000 (Bown and Rivera 2007). North of 38°S Lat, a relatively high frequency of wet years occurred in the 1940s–50s and 1980s–90s, whilst the opposite was evidenced in the 1960s–70s. Between 39° and 47°S a high frequency of dry years has occurred in the last three decades, which was preceded by a large number of wet years between 1960 and 1980 (Quintana 2004).

3. Remote sensing data sets

VNIR satellite imagery collected from Landsat MSS, Landsat TM, Landsat ETM+ and ASTER sensors, and SWIR data from ASTER, form the basis for our glacier inventories and for our analysis of recent variations on ice-capped volcanoes. The main selection criteria of satellite imagery included optical characteristics and acquisition dates (Kääb *et al* 2002). Optimal scenes contained minimal cloudiness and were acquired at the end of the ablation season, March–April in the austral hemisphere (Carrasco *et al* 2008). At this time of the year, the snow cover area is at a minimum extent, allowing a more precise delineation of glacier areas (Paul *et al* 2002).

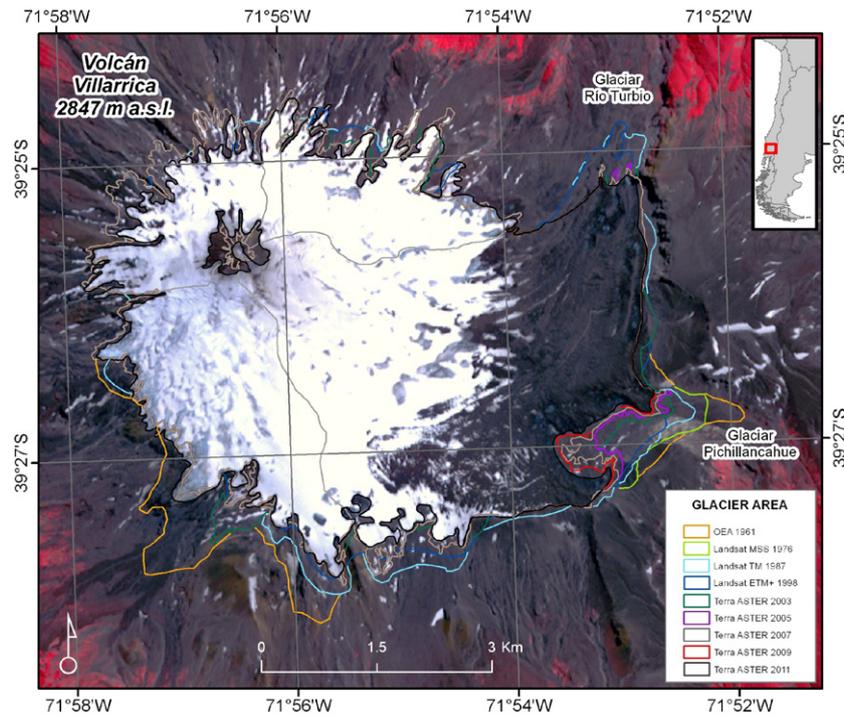


Figure 2. Volcán Villarrica areal changes 1961–2011. American State Organization (Organización de Estados Americanos, OEA) vertical aerial photograph from 1961. The other data sets are satellite images. The grey lines represent the main ice basins at Volcán Villarrica.

4. Methods

4.1. Georeferencing and image corrections

All maps and satellite images were converted to Universal Transversal Mercator (UTM) projection and World Geodetic System of 1984 (WGS84) datum allowing orthorectification using SRTM. The orthorectified Landsat MSS, TM and ETM+ imagery were co-registered to ASTER data by using the Cosi-Corr software (Leprince *et al* 2007) with subpixel error in co-registration between images.

4.2. Image classification

Several false-colour combination (FCC) images (based upon ASTER VNIR 1, 2, 3 and SWIR 4 bands) were generated by layer stacking using the available VNIR–SWIR satellite spectral bands (Sidjak and Wheate 1999).

Using histograms, adjusted by different threshold values, an accurate glacier classification was obtained. The best results were obtained with Landsat TM4/TM5 (Paul *et al* 2002) and ASTER VNIR 3/SWIR 4 band ratioed images (Kargel *et al* 2005). Furthermore, manual on-screen editing, essentially a manual smoothing, was performed to reduce the fractal structure along glacier boundaries (Rivera *et al* 2006). Once glacier areas are delineated, a comparison to previous datasets (aerial photographs) and historical records was completed in order to determine main glacier fluctuations. The glacier frontal changes are always calculated along the central flow line of each glacier.

Albedo changes of snow/ice facies due to volcanic ash deposition were analysed with VNIR ASTER data.

The distinction between areas experiencing albedo change due to volcanic activity and debris covered ice or rock outcrops/margins is difficult, but having a precise pre-eruption delineation of the glacier boundaries, a mask could be produced to restrict the albedo changes to the glacier surfaces allowing us to detect possible ablation enhancement of reduction, depending on the nature of the deposited ashes and, mainly, on the thickness of the falling material (Richardson and Brook 2010).

5. Results

Analysis of historical documents, aerial photographs and satellite images during recent decades indicated retreat for most of the regional glaciers (table 1).

5.1. Volcán Villarrica

At Volcán Villarrica (figure 2), the debris and ash covered Glaciar Pichillancahue-Turbio experienced an ice area reduction of 2.1 km² between 1961 and 2011 representing 13% of the 1961 glacier area, with a mean frontal retreat rate of -24.5 m yr^{-1} during the same period of time. The glacier areal and frontal changes at Villarrica are among the smallest compared to the other studied glaciers in the region (table 1), in spite of being one of the most active volcanoes of the country with several eruptive events in recent years when a large volume of fumarolic and eruptive materials were ejected (Clavero and Moreno 2004). This smaller change rate compared to other glaciers in the region (Masiokas *et al* 2009), is more likely related to the thick ashes and debris covering the

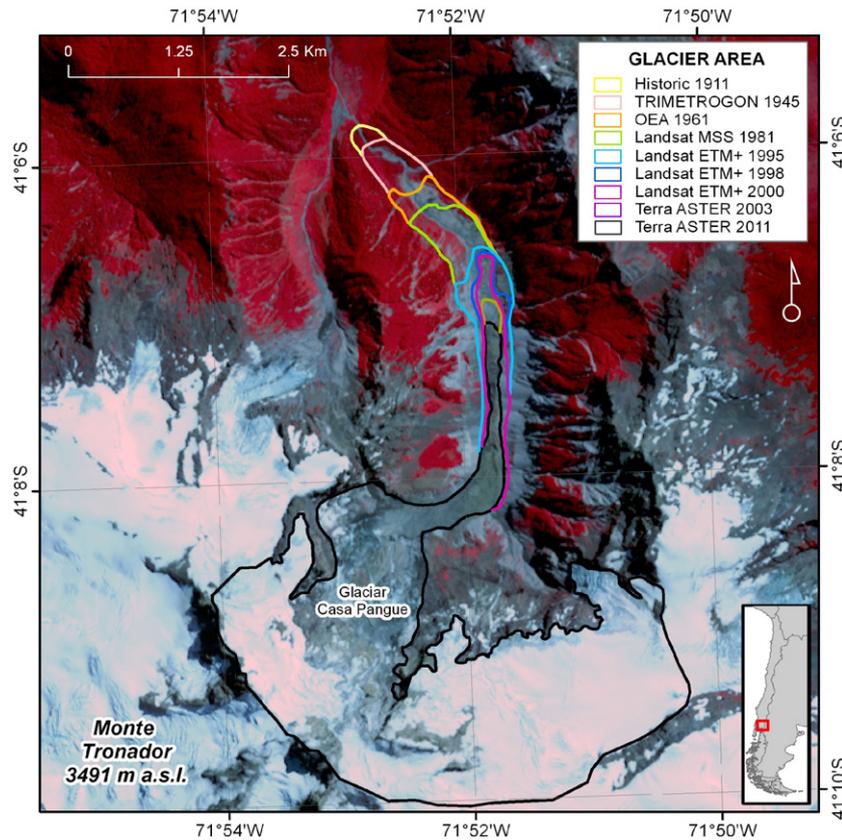


Figure 3. Glaciar Casa Pangué main frontal changes 1911–2011.

ablation area of the glacier reducing effective ice ablation, as demonstrated by Brock *et al* (2007) who described a critical thickness (Brook *et al* 2011) much smaller than other regions, due to the low thermal conductivity of the Villarrica tephra.

5.2. Monte Tronador

This non-active volcano (figure 3) is characterized by several glacier tongues flowing west and east from the Chile–Argentina border, some of them being heavily debris covered, especially the northern flank Glaciar Casa Pangué experiencing a significant decadal thinning (Bown and Rivera 2007) and a long-term frontal retreat between 1911 and 2007 (Masiokas *et al* 2009). In more recent years, the glacier continued thinning with the smallest area change rate compared to the other studied glaciers.

5.3. Monte Inexplorado

The glaciers of Monte Inexplorado have undergone strong retreats in recent decades (Masiokas *et al* 2009). Before the early 1990s, the main glacier (figure 4) was reaching low altitude at Río Blanco being fed by two ice accumulation basins. Since then, the glacier retreat resulted in two separated ice bodies (Inexplorado II and III), leaving behind a proglacial lake.

The combined area change of Glaciers Inexplorado II & III between 1961 and 2011 was $-0.13 \text{ km}^2 \text{ yr}^{-1}$, leaving a total ice area in 2011 of 26 km^2 (25% of the 1961 area).

The glacier with maximum retreats between 1961 and 2011 is Inexplorado II, with a rate of -125 m yr^{-1} .

5.4. Volcán Michinmahuida

At Volcán Michinmahuida (figure 5(a)) the four main glacier basins had a total ice area in 2011 of 48.1 km^2 , representing 89% of the total glacier area estimated for 1961. The maximum frontal retreat observed at Volcán Michinmahuida took place at Glaciar Amarillo (figure 5(b)), a glacier tongue aligned to the LOFZ (figure 1) that has been shrinking as all the other local glaciers (table 1). Glaciar Amarillo retreated between 1961 and 2007 at a rate of 76 m yr^{-1} . However, between November 2007 and September 2009, this glacier advanced $243 \pm 49 \text{ m}$. Interestingly, these advances were initially observed a few months before the beginning in May 2008 of an eruptive cycle of nearby Volcán Chaitén a glacier-free volcano located only 15 km to the west of Michinmahuida (figure 5(a)), connected by faults to Volcán Michinmahuida (López-Escobar *et al* 1995). This eruption generated a large volume of material, creating a layer of ash deposits with a thickness between 10 and 20 cm on top of ice-capped Volcán Michinmahuida (Alfano *et al* 2011), as well as across the entire region (Watt *et al* 2009) producing a drastic reduction in surface albedo (figure 6). These reductions were more significant on the western slopes of Michinmahuida, which were more directly receiving Volcán Chaitén ashes. The lower part of the glaciers, some of them already debris covered before the eruption, did not have

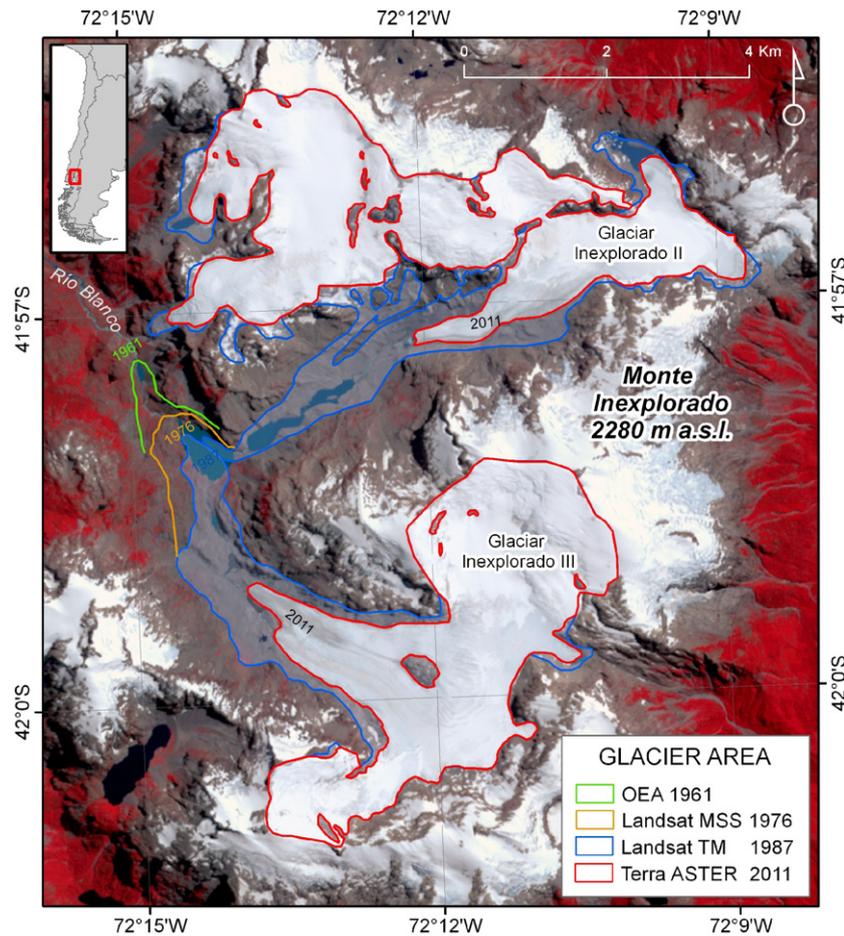


Figure 4. Monte Inexplorado glacier frontal changes 1961–2011. OEA is a vertical aerial photo from 1961. The other data sets are satellite images.

a significant albedo change, and some upper areas were probably covered by snow during or after the eruption, therefore the albedo changes in these areas were smaller.

6. Discussion

The ongoing climatic changes favour the long-term glacier variations in this region, characterized by ice thinning (Bown and Rivera 2007), area shrinkage and frontal retreats (Masiokas *et al* 2009). Glaciers located on active volcanoes have similar negative trends (figure 7) but different rates when compared to the variations of other glaciers located on top of non-volcanic mountains affected by the same climatic conditions.

For example, between 1961 and 2007, the main glacier of Monte Inexplorado retreated at a rate very similar to those of Volcán Michinmahuida. This mountain is only located 150 km north from Volcán Michinmahuida (figure 1), and its summit is only 170 m lower than that of Volcán Michinmahuida (table 1). However, the Glaciar Amarillo advance at Michinmahuida between 2007 and 2009 was not mirrored by the glaciers at Monte Inexplorado, which kept retreating until 2011, with an even higher rate of -339 m yr^{-1} (figure 7).

During recent years/decades, neither the regional climate record nor the glacier record of unceasing glacier retreat on non-volcanic Monte Inexplorado and Monte Tronador would appear to support a possible glacier advance in the region. Therefore, the observed glacier advance between 2007 and 2009 could be explained as a response to other factors including a possible surge event, or more likely, the active condition of Volcán Michinmahuida and the recent eruption of Volcán Chaitén.

The ashes produced by the Volcán Chaitén eruption have been spread by wind mainly towards the east creating a thick layer of deposits over the region, where the glaciers at Volcán Michinmahuida have also been affected (Watt *et al* 2009, Alfano *et al* 2011). The ash cover has produced a drastic reduction in surface albedo (figure 6) as expected from any glacier surface (characterized by higher spectral reflectance) when covered by minerals, ash and dust (Brock *et al* 2007). This albedo reduction at Volcán Michinmahuida was confirmed by comparing an ASTER image collected from before the eruption, on 27 January 2006, with an ASTER image from 19 January 2009, where widespread tephra layers covering the ice surface were detected, yielding a significant decrease in surface albedo, especially on altitudes between 1500 and 2000 m asl and western slopes of the volcanic edifice.

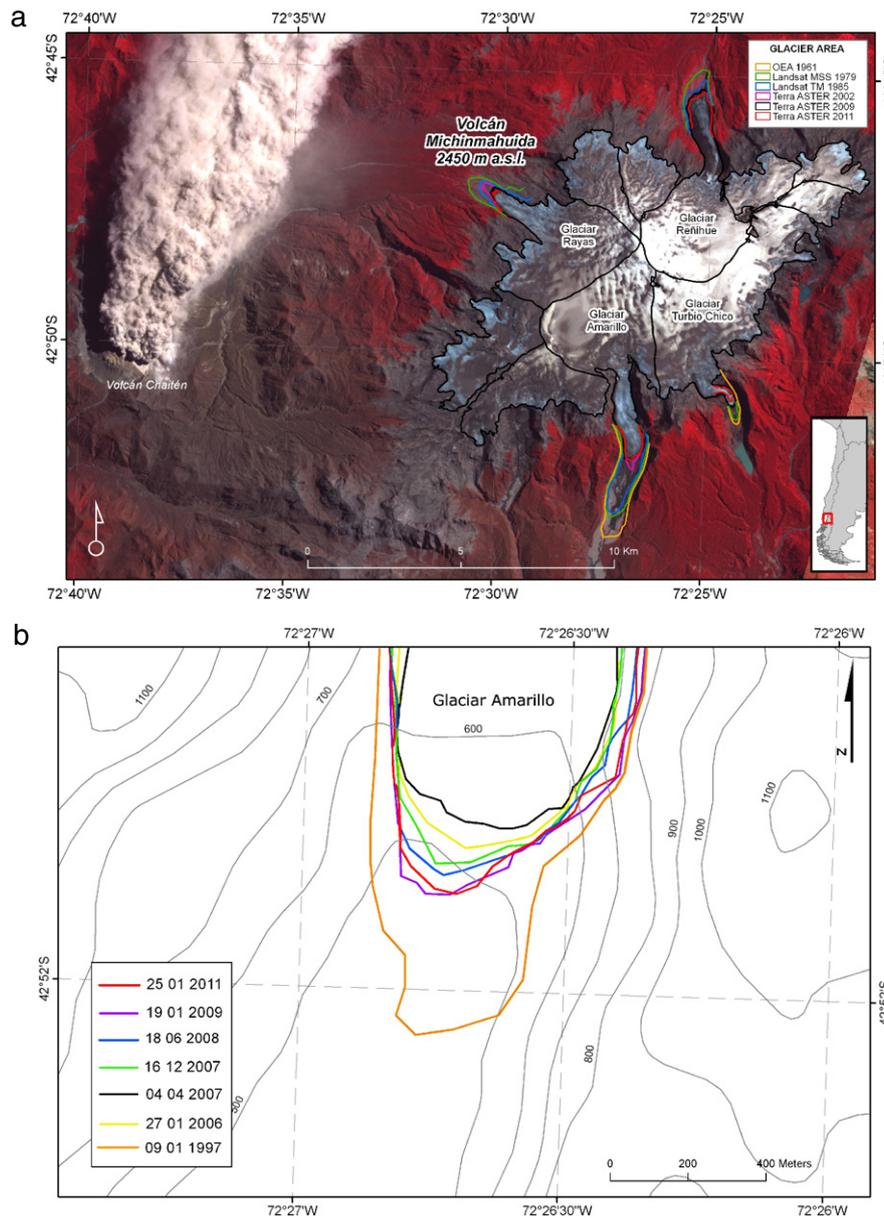


Figure 5. (a) ASTER VNIR 321 image from 19 January 2009 obtained during the eruption of Volcán Chaitén. The ash plume is directed towards ice-capped Volcán Michinmahuida, where the main glacier frontal changes 1961–2011 are shown. (b) Frontal variations since 1997 of Glaciar Amarillo, where the 2007–09 advance is clearly visible.

Considering the above, a glacier advance could have been explained by an increase of snow melting at the surface of the glacier (due to albedo reduction) that led to increased basal sliding when melt water penetrated down to the glacier bedrock, thereby reducing basal shear stress. However, glacier advances at Michinmahuida began several months before the eruption inception, therefore the albedo changes are not responsible for the observed advances. Even more, the ablation changes due to the albedo decreases are not expected to be major, because the reported ash thickness are, more likely, insulating the underlying snow/ice.

An alternative hypothesis is related to enhance geothermal heat flux at some bedrock spots of the Michinmahuida icecap. If this is the case, increasing meltwater will provoke higher basal water pressure leading to its rapid release

(Gudmundsson *et al* 1997). Higher amounts of meltwater at the glacier bed can lead to enhance basal sliding and therefore produce higher velocities or glacier advances. However, in temperate glaciers like Michinmahuida, this process does not necessarily result in glacier surges, because the bed is already wet and sliding is a predominant factor. In spite of this temperate condition, ice velocities at the lower part of Glaciar Amarillo were obtained by applying a feature tracking procedure (Scambos *et al* 1992) based upon ASTER images (figure 8). The resulting vectors show higher velocities during the advancing period of 2007–09 compared to 2009–11, when the glacier was more stable. The lower coherence between images obtained during the advancing period is responsible for the small number of velocity vectors (left panel) compared to the more recent period. The decrease in ice velocities

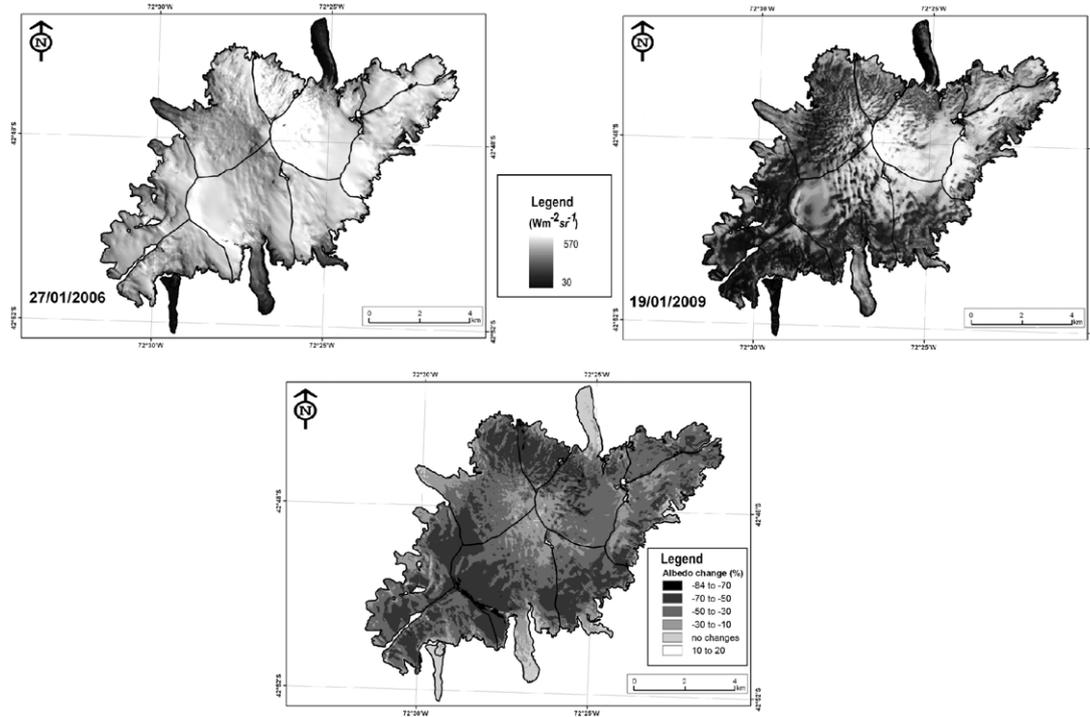


Figure 6. Radiance scenes from Volcán Michinmahuida as derived from ASTER VNIR 1 images from 2006, before Chaitén eruption (upper left) and during the eruption in 2009 (upper right). At the bottom, albedo differences (in percentage) between 2006 and 2009.

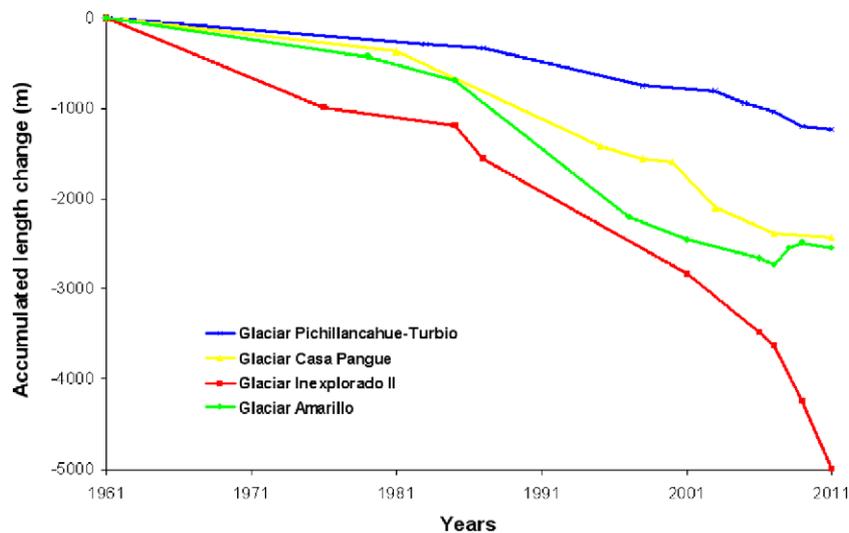


Figure 7. Compilation of recent glacier variations in the study area.

between 2009 and 2011 could indicate a dynamic component in the explanation of the glacier advance process.

The existence of hot spots at Michinmahuida is possible, because it is an active volcano located at the LOFZ, and because it is linked to nearby Volcán Chaitén by geologic faults and parasitic cones. If the detected glacier advance is connected to enhance subsurface geothermal fluxes prior the eruption, this process will be only a ‘temporal’ response. However, a unique feature among the downstream valleys of Michinmahuida is the lack of vegetation at the Glaciar Amarillo valley, indicating frequent mudflows coming from

the glacier. During the Chaitén eruption, the satellite image from 19 January 2009 clearly shows a lahar type of deposit at this valley, which must have been generated by a sudden melt of the ice. This flood event was described by Alfano *et al* (2011) who visited the area in January 2009. This process could be related to the existence of enhanced subglacial volcanic activity at Michinmahuida producing high quantities of meltwater, or to rainfall removing ashes deposited on top of the glacier, which combined with higher ablation resulted in a flood.

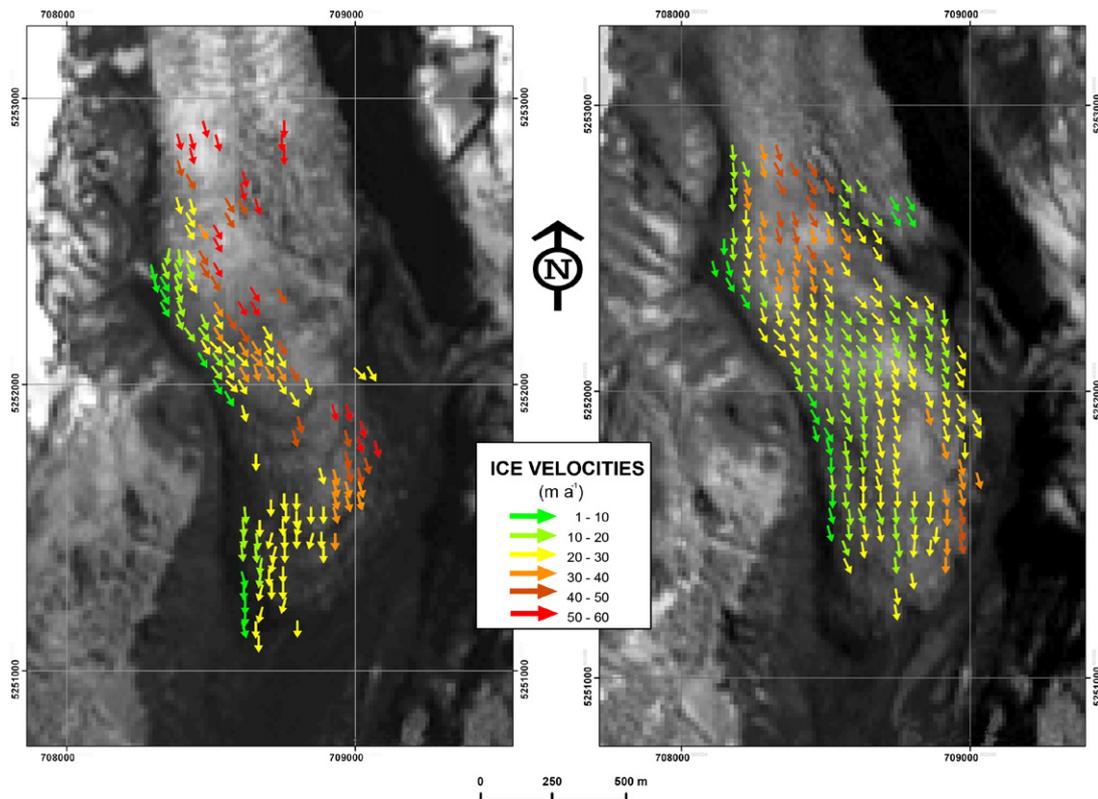


Figure 8. Ice velocities (m yr^{-1}) at Glaciar Amarillo’s lower tongue. The left panel shows the velocities obtained during the glacier advance (December 2007 and January 2009). The right panel shows the results between January 2009 and January 2011 (after the main glacier advance). UTM-WGS84 co-ordinates.

7. Conclusions

Glaciers primarily respond to prevailing atmospheric conditions, with a time delay dependent upon glacier length, mass balance and ice thickness. On a decadal timescale, the glaciers of Southern Chile are responding to the changing climate of the region that includes reduced precipitation and tropospheric warming.

There are no significant recent climatic anomalies or trends which could explain the ice advances observed at Volcán Michinmahuida. This suggests that the behaviour of these glaciers is also driven by non-climatic factors, namely volcanic activity associated with the eruption of Volcán Chaitén located a few kilometres to the west of Volcán Michinmahuida.

As the Michinmahuida glacier advances began a few months before the eruption of Volcán Chaitén, the increased ice flow could be a response to higher subsurface geothermal heat fluxes prior to the inception of the eruption. If heating at the bedrock of this glacier increased, leading to the generation of basal meltwater, it is possible that enhanced basal sliding would occur, resulting in a sudden glacier advance. This hypothesis is also sustained by the lack of vegetation at the downstream valley of Glaciar Amarillo, indicating lahar kind of mudflows due to sudden melting events. No other downstream valleys of Michinmahuida have similar features, indicating a feature possibly connected to a geothermal heat flux spot. In spite of the almost synchronous events (volcanic

eruption and glacier advance separated by a few months), much more work is required to determine the causes of present glacier behaviour.

The described results indicate that the primary factor in the glacier behaviour in Southern Chile is clearly the regional climate change observed during most of the twentieth century. The secondary factor, but maybe dominating at certain volcanoes, is the volcanic activity, which may have a significant role in altering long-term trends or disrupting linear responses as suggested from anomalous ice advances in recent years.

Although the satellite imagery analysed in this research is a key contribution to better understanding glacier variations in volcanic environments, more *in situ* field studies are required to determine the precise relationships between glacier behaviour and current regional volcanism, as well as testing the presented hypothesis.

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References

- Alfano F, Bonadonna C, Volentik A, Connor Ch, Watt S, Pyle D and Connor L 2011 Tephra stratigraphy and eruptive volume of the May, 2008, Chaitén eruption, Chile *Bull. Volcanol.* **73** 613–30
- Bown F and Rivera A 2007 Climate changes and recent glacier behaviour in the Chilean Lake District *Glob. Planet. Change* **59** 79–86
- Brock B, Rivera A, Casassa G, Bown F and Acuña C 2007 The surface energy balance of an active ice-covered volcano: Villarrica volcano, Southern Chile *Ann. Glaciol.* **45** 104–14
- Brook M, Dean J and Keys J 2011 Response of a mid-latitude cirque glacier to climate over the last two decades: Mangaehuehu glacier, Mt Ruapehu *Earth Surf. Process. Landforms* **36** 1973–80
- Carrasco J, Casassa G and Quintana J 2005 Changes of the 0 °C isotherm and the equilibrium line altitude in central Chile during the last quarter of the 20th century *Hydrol. Sci. J.* **50** 933–48
- Carrasco J, Osorio R and Casassa G 2008 Secular trend of the equilibrium-line altitude on the western side of the southern Andes, derived from radiosonde and surface observations *J. Glaciol.* **54** 538–50
- Cembrano J, Schermer E, Lavenu A and Sanhueza A 2000 Contrasting nature of deformation along an intra-arc shear zone, the Liquine-Ofqui fault zone, southern Chilean Andes *Tectonophysics* **319** 129–49
- Clavero J and Moreno H 2004 Evolution of Villarrica Volcano *Revista Sernageomin* **61** 17–27
- Falvey M and Garreaud R 2009 Regional cooling in a warming world: recent temperature trends in the Southeast Pacific and along the West Coast of Subtropical South America (1979–2006) *J. Geophys. Res.* **114** D04102
- González-Ferrán O 1995 *Volcanes de Chile Santiago* (Santiago: Instituto Geográfico Militar)
- Gudmundsson M T, Sigmundsson F and Björnsson H 1997 Ice–volcano interaction of the 1996 Gjalp subglacial eruption, Vatnajökull, Iceland *Nature* **389** 954–7
- Kääb A, Paul F, Maish M, Hoelzle M and Haerberli W 2002 The new remote sensing derived Swiss glacier inventory: II. First results *Ann. Glaciol.* **34** 362–6
- Kargel J et al 2005 Multispectral imaging contributions to global land ice measurements from space *Remote Sens. Environ.* **99** 187–219
- Lara L 2009 The 2008 eruption of the Chaitén volcano, Chile: a preliminary report *Andean Geol.* **36** 125–9
- Leprince S, Barbot S, Ayoub F and Avouac J P 2007 Automatic and precise orthorectification, coregistration, and subpixel correlation of satellite images, application to ground deformation measurements *IEEE Trans. Geosci. Remote Sens.* **45** 1529–58
- López-Escobar L, Cembrano J and Moreno H 1995 Geochemistry and tectonics of the Chilean Southern Andes basaltic Quaternary volcanism (37–46°S) *Rev. Geol. Chile* **22** 219–34
- Masiokas M, Rivera A, Espizúa L, Villalba R, Delgado S and Aravena J C 2009 Glacier fluctuations in extratropical South America during the past 1000 years *Palaeogeogr., Palaeoclimatol., Palaeoecol.* **281** 242–68
- Mason B G, Pyle D M and Oppenheimer C 2004 The size and frequency of the largest explosive eruptions on Earth *Bull. Volcanol.* **66** 735–48
- Paul F, Kääb A, Maish M, Kellenberger T and Haerberli W 2002 The new remote-sensing-derived Swiss glacier inventory: I. Methods *Ann. Glaciol.* **34** 355–61
- Quintana J 2004 Estudio de los factores que explican la variabilidad de la precipitación en Chile en escalas de tiempo interdecadal *MSc Thesis* University of Chile
- Richardson J and Brook M 2010 Ablation of debris-covered ice: Some effects of the 25 September 2007 Mt Ruapehu eruption *J. R. Soc. New Zealand* **40** 45–55
- Rivera A, Bown F, Casassa G, Acuña C and Clavero J 2005 Glacier shrinkage and negative mass balance in the Chilean Lake District (40°S) *Hydrol. Sci. J.* **50** 963–74
- Rivera A, Bown F, Mella R, Wendt J, Casassa G, Acuña C, Rignot E, Clavero J and Brock B 2006 Ice volumetric changes on active volcanoes in southern Chile *Ann. Glaciol.* **43** 111–22
- Rivera A, Corripio J G, Brock B, Clavero J and Wendt J 2008 Monitoring ice capped active Volcán Villarrica in southern Chile by means of terrestrial photography combined with automatic weather stations and GPS *J. Glaciol.* **53** 920–30
- Rosenblüth B, Fuenzalida H and Aceituno P 1997 Recent temperature variations in South America *Int. J. Climatol.* **17** 67–85
- Rütlant J and Fuenzalida H 1991 Synoptic aspects of the central Chile rainfall variability associated with the southern oscillation *Int. J. Climatol.* **11** 63–76
- Salamantin A, Murav'yev Y, Shiraiwa T and Matsuoka K 2000 Modelling dynamics of glaciers in volcanic craters *J. Glaciol.* **46** 177–87
- Scambos T, Dutkiewicz M, Wilson J and Bindshadler R 1992 Application of image cross-correlation to the measurement of glacier velocity using satellite image data *Remote Sens. Environ.* **42** 177–86
- Sidjak R and Wheate R 1999 Glacier mapping of the Illecillewaet icefield, British Columbia, Canada, using Landsat TM and digital elevation data *J. Remote Sens.* **20** 273–84
- Simkin T and Siebert L 1994 *Volcanoes of the World* 2nd edn (Tucson, AZ: Geoscience Press) p 349
- Stern Ch 2004 Active Andean volcanism: its geologic and tectonic setting *Rev. Geol. Chile* **31** 161–206
- Watt S F L, Pyle D M, Mather T A, Martin R S and Matthews N E 2009 Fallout and distribution of volcanic ash over Argentina following the May 2008 explosive eruption of Chaitén, Chile *J. Geophys. Res.* **114** B04207