Climate change and land ice

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Glaciers provide excellent records of climate change. Samples of particulates and gases can be extracted from ice cores, from which the past composition of the atmosphere can be reconstructed. Ice cores also record temperature and moisture, and all of this information is stored in dateable, consecutive layers. The position of end moraines, past and present, can be used to discern past glacier positions, and these deposits can be dated with radiogenic isotopes to reveal the timing of past shifts in climate. The response of a glacier to climate change may be fairly immediate for alpine cirque glaciers, but a response time is usually involved, ranging from decades for valley glaciers to thousands of years for ice sheets. Long-narrow glaciers will have a longer response time than will compact ice caps of the same area. A negative mass balance may cause an immediate response in the position of the glacier snout, but a positive regime may not be detected at the snout for many years. Weekly, monthly, and seasonal variations in glaciers are especially sensitive to ablation rates and meltwater lubrication. Glacier response over years and decades is tied to mass balance, which reflects a range of climate conditions, especially as influenced by ocean temperatures and position of the jet stream. Glacier response also depends on the distribution of glacier area with elevation. As climate warms, the elevation of the snow line will progressively experience upstream migration, shifting precipitation from solid to liquid on low-altitude glaciers. In this context, a small mountain glacier with most of its area at lower elevations will experience retreat and thinning due to rain. However, a valley glacier with an important accumulation area at higher elevations will experience stability or even thickening if the maximum snowfall is also migrating upstream. Thus, glaciers with bigger and higher elevation accumulation areas may advance during periods of climate warming, whilst small glaciers without high-altitude areas will more likely tend to disappear if ongoing climate trends persist over time.

Scientists have incomplete geographic coverage for monitoring long-term glacier changes, especially for cold-ice glaciers in the high latitudes. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) provided enough evidence of human-induced climate change, especially in connection to the generation of greenhouse gases such as CO_2, which has increased 40% since 1750 (IPCC 2013). According to the same IPCC report, worldwide glaciers continued to shrink in the past decade, as revealed by time series of changes in glacier length, area, volume, and mass. In a global context of glacier area reduction, an outline of glacier changes taking place in the extra-tropical Andes of Chile and Argentina since 1985 is presented.

The selected glaciers are located from the northern arid zone down to the humid and cold

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southern tip of South America (Figure 1), and their areal changes have been mapped between 1985/1986 and the most recent cloud-free available satellite image (Table 1).

Methods

Variations in glacial areas have been obtained through a comparison of several satellite images, acquired for all the selected glaciers. The glacier outlines have been obtained by analyzing false color composite scenes produced from Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper (ETM), and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) bands. The outlines were manually digitalized using ArcGIS commercial software.

The error of the glacial area calculation was estimated by multiplying the pixel size, or image resolution, by the perimeter of the digitized polygon. The average relative error for each zone varies between ±0.2% and ±12%.

Finally, the temperature reanalysis data from NCEP-NCAR (National Centers for Environmental Prediction-National Center for Atmospheric Research) is compared with the observed glacier area changes. NCEP-NCAR reanalysis data corresponds to monthly mean values at the pressure level close to the altitude of each glacier area (Table 1). The annual mean and anomalies estimations have been calculated with respect to the 1977–2006 mean.

General overview of Chilean glaciers, climate, and climate changes

The water cadastre (Dirección General de Aguas) of the public works ministry (DGA 2013) of Chile is the governmental institution in charge of updating the Chilean glacier inventory. Recent figures they have for the total number of Chilean glaciers is 24 114 with a total area of 23 460 km^2 (2013). This inventory includes any ice body bigger than 0.01 km^2, including rock glaciers, glaciarets, debris-covered ice, and clean ice. These glaciers are distributed from 18°S down to 55°S and experience a contrast of climatic conditions, from areas with only a few millimeters of precipitation per year along the Atacama Desert in northern Chile, to more than 3000 mm along the islands facing the Pacific in the southern part of the country (Quintana and Aceituno 2012).

Glaciers located in northern Chile, at high altitude, are characterized by cold ice, little summer melting, high sublimation, and very low ice velocities. Located in a dry environment, these glaciers are more sensitive to precipitation changes, with sublimation being the main process defining ablation; therefore, these glaciers are particularly sensitive to changes in atmospheric humidity which affect the ratio between sublimation and melting at the ice surface. Conversely, glaciers located in southern Chile, under wet and cold conditions, are more sensitive to temperature changes because ablation is mostly dominated by melting. These characteristics of the ablation process define somewhat the different sensitivity of glaciers located at the same latitudes in the Andes in response to orographic effects.

Changes in temperature have a double influence on glacier mass balance: first, they affect the amount of energy available for the melting process; and second, the air temperature determines whether precipitation falls as snow or rain, defining the amount of accumulation during the hydrological year. However, the effect of changes in air temperature depends on the 0°C isotherm position, since an increase in air temperature will not affect the mass balance of a glacier until the freezing line reaches the elevation of that glacier.

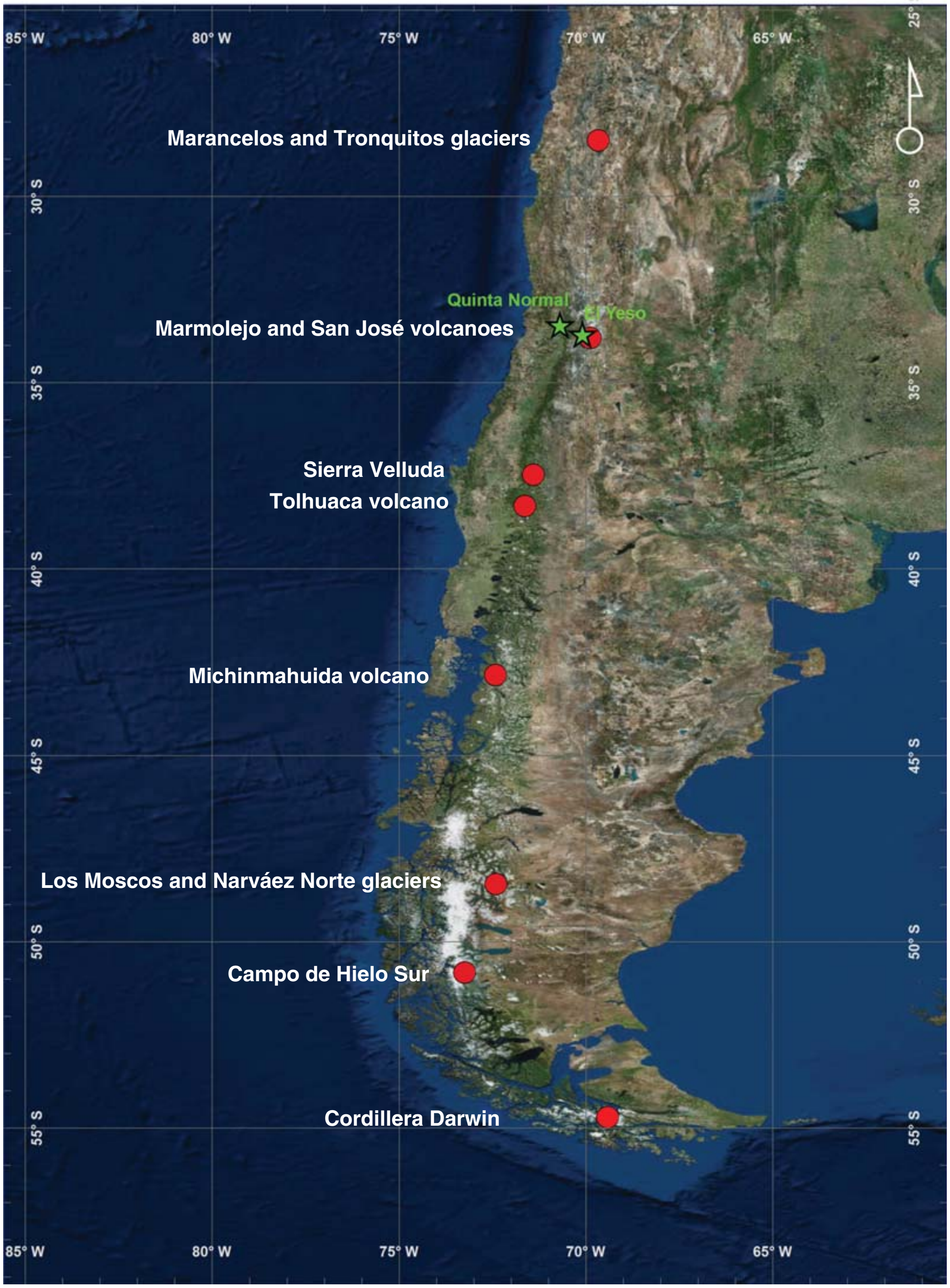

Figure 1 Location map of selected glaciers.

Table 1 Glacier areas.

Glacier areas (number of studied glaciers per area)	Region	Glacier type	Area changes Initial (km^2)	Final (km^2)	Mean altitude (m asl)	Studied period	Total % of area change
Maranceles and Tronquitos (7)	Northern Chile	Mountain	15.9	9.4	5263	1985–2013	−41
Volcán Marmolejo and San José (5)	Central Chile	Ice-capped volcanoes	22.3	21.1	4653	1986–2013	−5
Sierra Velluda (8)	Chilean Lake District	Mountain	19.0	11.4	2666	1985–2014	−40
Volcán Tolhuaca (3)	Chilean Lake District	Ice-capped volcano	3.1	1.5	2424	1985–2014	−50
Volcán Michinmahuida (4)	Northern Patagonia	Ice-capped volcano	39.7	36.2	1758	1985–2013	−9
Los Moscos and Narváez Norte (3)	Central Patagonia	Valley	21.5	18.9	1483	1985–2014	−12
Torres del Paine (5)	Southern Patagonia	Freshwater calving	423.1	380.4	1284	1986–2014	−11
Cordillera Darwin (6)	Tierra del Fuego	Tidewater calving	129.9	118.6	1044	1986–2014	−10

For instance, in northern Chile, where glaciers are far above the 0°C isotherm, an increase or decrease in temperature probably would have a scarce effect on the mass balance; by comparison, a change in precipitation is likely to strongly affect the net mass balance of such glaciers.

Recent climate change in Chile

Several studies indicate that air temperatures in Chile have warmed in recent decades. However, the spatial pattern of these temperature changes exhibits a considerable variability. In situ radiosonde and satellite information from 1979 onwards indicates a marked cooling (−0.20°C/decade) along the coast of north-central Chile between 17°S and 37°S, and a marked warming (0.25°C/decade) inland and over the Andean slope (Falvey and Garreaud 2009). In southern Chile (38°S to 48°S), temperature trends over land are weak and do not show a clear identifiable spatial pattern (Falvey and Garreaud 2009). By comparison, in the Chilean Lake District (38–42°S) the surface temperature trend exhibits a cooling in the second half of the twentieth century; nevertheless, in the middle to upper troposphere, radiosonde data from Puerto Montt show a warming trend between 0.019°C a^{-1} and 0.031°C a^{-1} (Bown and Rivera 2007). This warming is demonstrated by the increase of the 0°C isotherm elevation in central Chile, both in summer (200 ± 6 m) and in winter (122 ± 8 m) (Carrasco, Casassa, and Quintana 2005). All these observed data suggest that mid-troposphere warming is the main cause of glacier retreat along the Chilean Andes.

In Chile, precipitation trend changes are clearer south of 30°S. For instance, Quintana and Aceituno (2012) detected a negative trend in annual precipitation between 30°S and 43°S from the beginning of the twentieth century. Between 30°S and 35°S annual rainfall showed a persistent negative trend from the beginning of the twentieth century until the mid-1970s, followed by a significant increase in the 1980s; since then, the rainfall regime has exhibited a marked decadal variability in the absence of a well-defined trend (Quintana and Aceituno 2012). Between 37°S and 43°S a downward trend in annual precipitation is detected from 1950. This trend is, however, interrupted by a positive trend in the mid-1970s, registered by all the stations taken into account, except between 40°S and 43°S. In general, annual precipitation rates between 37°S and 47°S have reduced since 1950. This negative trend intensified in the last part of the twentieth century (Quintana and Aceituno 2012). According to Garreaud *et al.* (2013) a tendency for weaker westerlies has been detected at mid-latitudes (approx. 45°S); meanwhile, around 60°S, an increase in westerlies prevails. This tendency in the westerlies accounts for a decrease of 300–800 mm/decade over north-central Patagonia and an increase of approximately 200 mm/decade further south (50°S and beyond).

Independently from the changes in precipitation, the warming detected over the Patagonian ice field has caused a decrease in the amount of solid precipitation.

Recent decadal glaciers changes

Semiarid northern Chile

The Maranceles (28°25'S/69°40'W) and Tronquitos (28°32'S/69°43'W) glaciers are located in the dry Andes of northern Chile, at very high altitude from 4800 to almost 5800 m asl. These mountain glaciers have suffered important areal reductions, with a total loss of 41% since 1985.

Mediterranean central Chile

The Marmolejo (33°44'S/69°55W) and San José (33°49'S/69°54'W) glaciers are contributing meltwater to the Maipo basin located in the central zone of Chile near Santiago, Chile's capital. These glaciers are located on the western and southern flanks of active volcanoes that have not experienced any eruptive events since the beginning of the nineteenth century. The Marmolejo and San José glaciers have an extended altitudinal range (between 3500 and almost 6000 m asl), and have suffered some of the smallest changes within the studied glaciers, with areal losses of 5% since 1986.

Chilean Lake District

The glaciers in Sierra Velluda (37°28'S/71°25'W) and at Tolhuaca volcano (38°19'S/71°39'W) in the Lake District, have smaller altitudinal ranges than those in central Chile, ranging between 2000 and 3250 m asl. This is due to a generally lower altitude Cordillera, interrupted by few volcanoes rising above 3000 m asl. Sierra Velluda is partially covered by several mountain glaciers, all of them experiencing strong area shrinkage, with a total area loss of 40% since 1985 (Figure 2). The active Tolhuaca volcano is also partially covered by mountain glaciers, showing the strongest areal reduction of this study, with areal losses of 50% since 1985.

Northern Patagonia

Active ice-capped Volcán Michinmahuida (42°48'S/72°27'W) has experienced a total areal loss of 9% since 1985. This area shrinkage

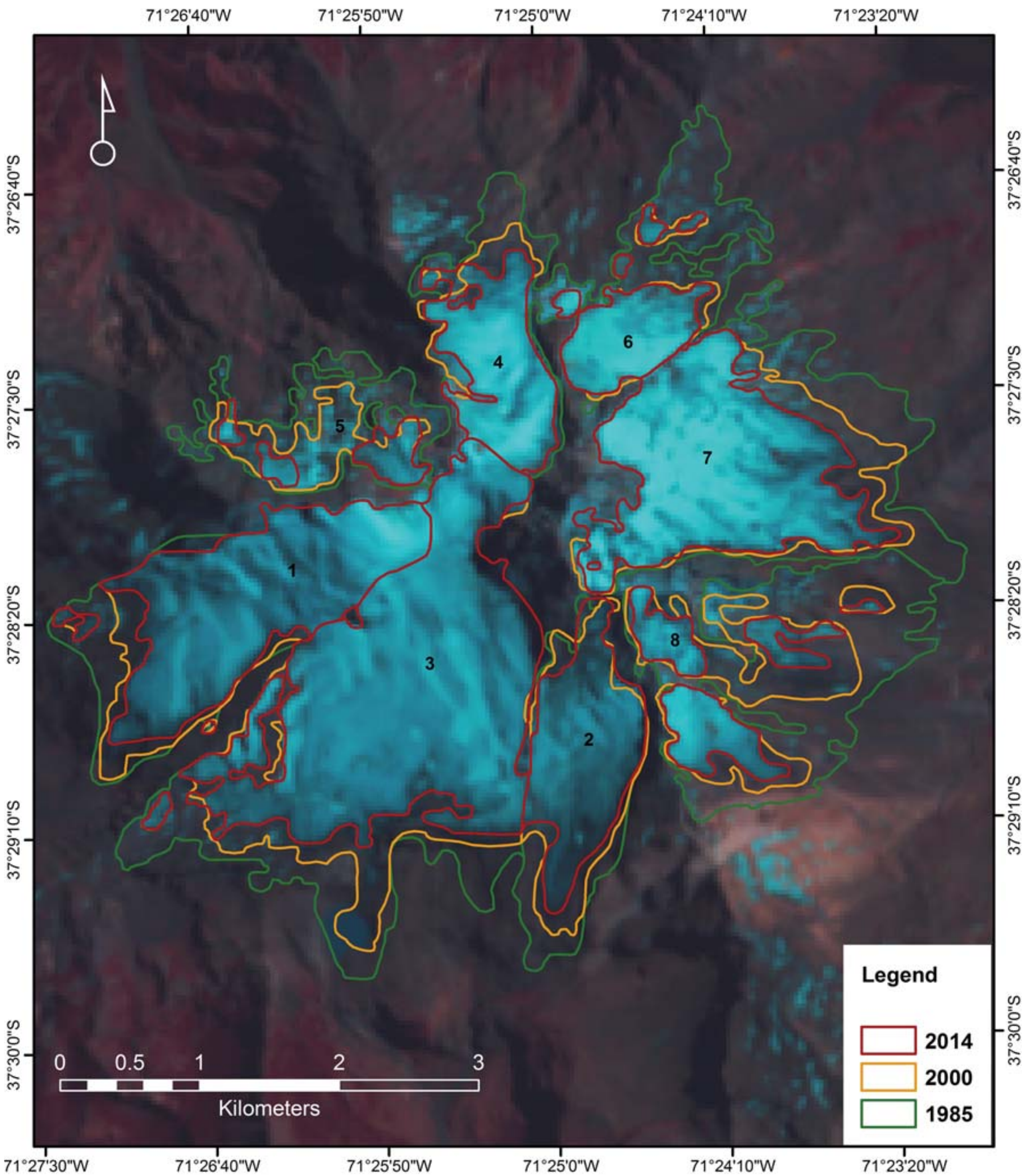

Figure 2 Sierra Velluda glacier changes (Chile).

is similar to the changes observed by Rivera and Bown (2013) in other ice-capped active volcanoes of the region.

Central Patagonia, Los Moscos

In central Patagonia, the Los Moscos mountain complex (48°25'S/72°25'W) is situated at the border between Chile and Argentina. This mountain complex is covered by several valley glaciers that have experienced retreat since the first aerial photographs from 1944/1945. A total area loss of 12% has been observed since 1985. On the Chilean side, the Mosco 1 and 2 glaciers (Figure 3) were merged in 1985; however, at present, due to frontal retreat they are completely separated. On the Argentinean side, the Narváez Norte glacier was calving into a lake in 1985, but at present the glacier front is noncalving (Figure 3).

Southern Patagonia, Campo de Hielo Sur

Campo de Hielo Sur (Southern Patagonian Ice Field) is a large glacier complex spanning from 48.3°S to 51.6°S, considered the biggest temperate ice field in the Southern Hemisphere, with almost 12 500 km^2 of ice (DGA 2013). In the southern end of this ice field (50–51°S), at the Torres del Paine National Park of Chile and at the Los Glaciares National Park of Argentina, five glaciers located in the eastern side have been selected for this study: Grey, Olvidado, Dickson, Cubo, and Frías (Figures 4 and 5). Their historical (since the Little Ice Age) elevation, frontal, and areal changes were studied in detail by Rivera and Casassa (2004), and here all these glacier areal changes have been updated up to 2014.

The selected glaciers in this region have experienced a total area loss of 11% (42.7 km^2) since 1986, a higher percentage compared to the changes obtained by Rivera and Casassa (2004) between 1945 and 2000 (8%). All of these glaciers are at present calving into freshwater lakes; however, at the beginning of the series, in 1986, the Dickson glacier had two arms, a freshwater calving front to the south and a noncalving arm to the north, which were merged together at that time with the Frías and Cubo glaciers. In 1986 only small proglacial lagoons were visible at the common debris-covered front between Frías, Cubo, and Dickson's northern arm. Now, all are clearly separated with both arms of the Dickson glacier calving into an expanded Dickson lake, where the Cubo glacier is also calving (Figure 4). The Frías glacier is completely separated from the two other glaciers, having a debris-covered lower tongue that is partially calving into several lagoons that are progressively increasing their size. This glacier experienced shrinkage at a rate of 0.3 km^2/year between 2000 and 2014, almost three times the rate recorded between 1945 and 2000, of 0.11 km^2/year (Rivera and Casassa 2004).

Dickson glacier's southern arm has been calving into the homonymous lake since the Little Ice Age (Figure 4). In total, the Dickson glacier reduced its area at a rate of 0.35 km^2/year between 2000 and 2014, an accelerated rate when compared to the 0.15 km^2/year observed between 1945 and 1975, 0.3 km^2/year between 1975 and 1986, and 0.17 km^2/year between 1986 and 2000 (Rivera and Casassa 2004).

Located a few kilometers further south, the Grey glacier is calving into its homonymous lake (Figure 5). The lower tongue of Grey has two calving fronts separated by an island where trim lines are clearly visible, showing the retreat and thinning since the Little Ice Age. Of all the selected glaciers in this study, the Grey glacier has experienced the largest area shrinkage during the observation period (a total loss of 19.2 km^2, or 7% of its 1986 area). Areal reduction rates reached 0.71 km^2/year between 2000

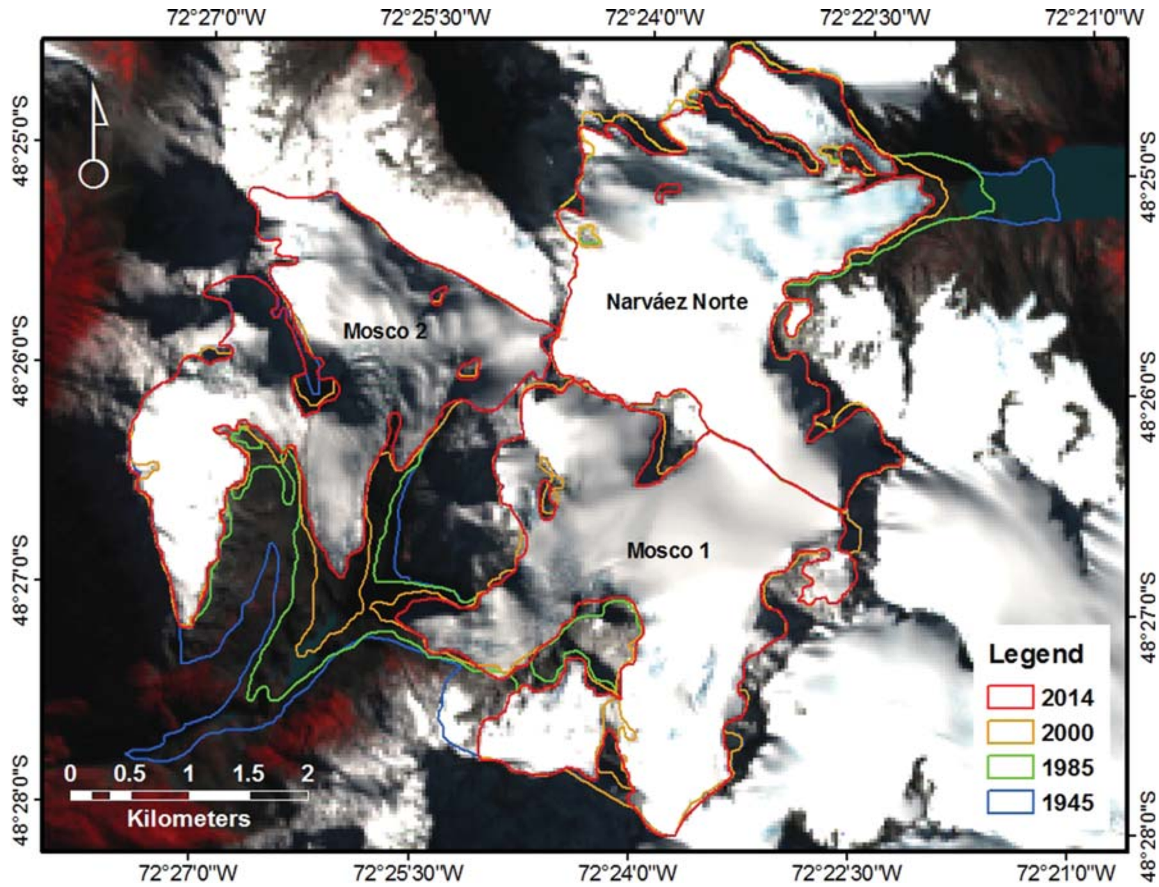

Figure 3 Recent changes in the Los Moscos (Chile) and Narváez Norte (Argentina) glaciers.

and 2014, again accelerated when compared to the 0.15 km^2/year observed between 1945 and 1975, 0.27 km^2/year between 1975 and 1986, and 0.46 km^2/year between 1986 and 2000 (Rivera and Casassa 2004).

A couple of kilometers north from Grey is the Olvidado glacier (Figure 5), which in 1986 was a valley glacier without any adjoining water body. At present, as a result of retreat, a small lake has formed next to the frontal position into which the glacier now calves. This glacier has lost almost 16% (3.6 km^2) of its 1986 area, and has retreated at a rate of 62 m/year between 2000 and 2014, more than twice the rates observed between 1945 and 1975 (25 m/year) and 1975 and 2000 (29 m/year) (Rivera and Casassa 2004).

Tierra del Fuego, Cordillera Darwin

The Cordillera Darwin ice field is located in the main range of Isla de Tierra del Fuego in southern Chile (55°S). Six tidewater calving glaciers have been selected for this study (Figure 6), all of them located at the end of the Parry fjord. Most of these glaciers have been relatively stable since 1986; however, the biggest glacier (Darwin, 54°42'W/69°29'W, 41.5 km^2 in 2014) suffered a strong frontal retreat (almost

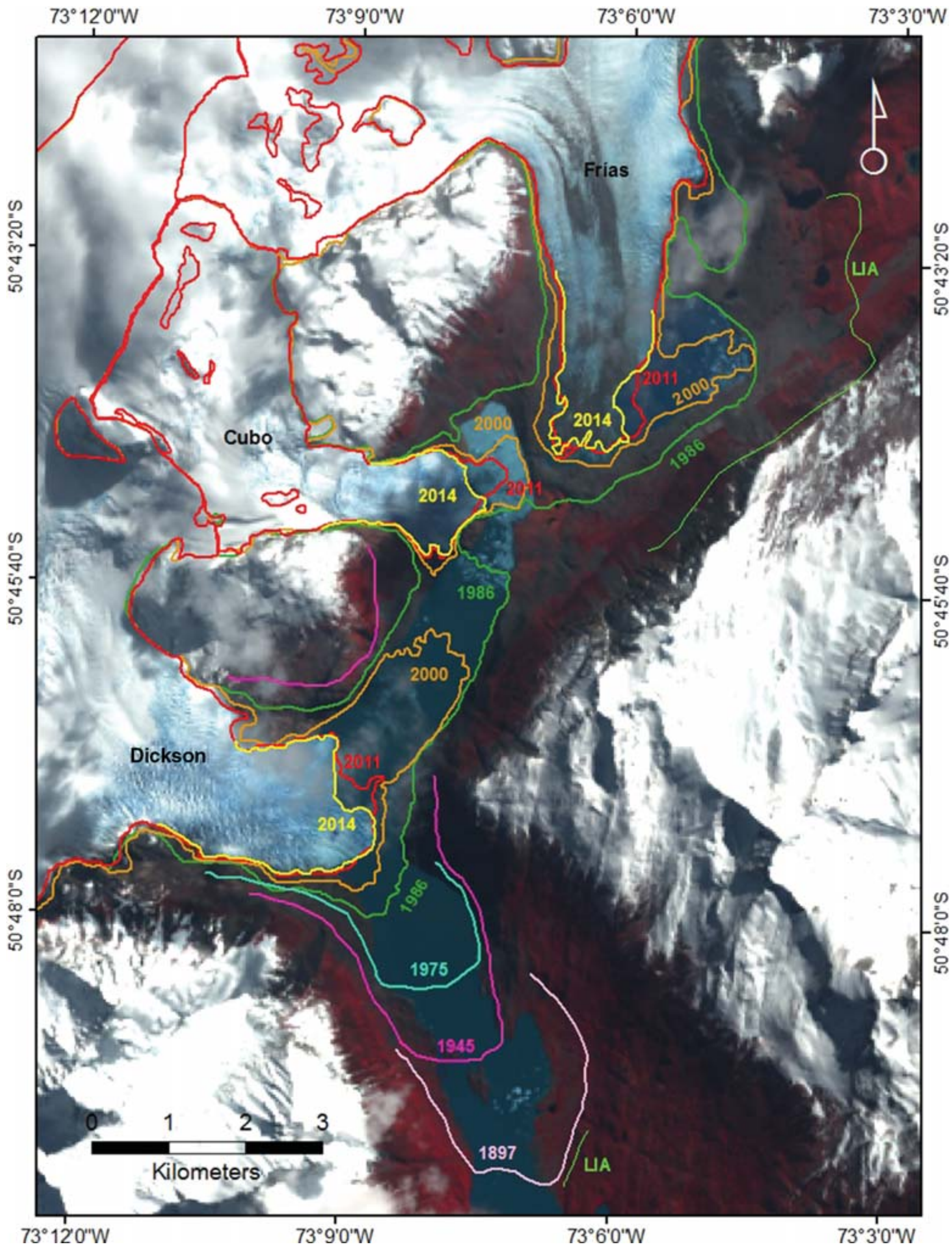

Figure 4 Dickson (Torres del Paine National Park, Chile), Cubo, and Frías (Los Glaciares National Park, Argentina) glaciers. Pre-1985 data from Rivera and Casassa 2004. Reproduced from Regents of the University of Colorado.

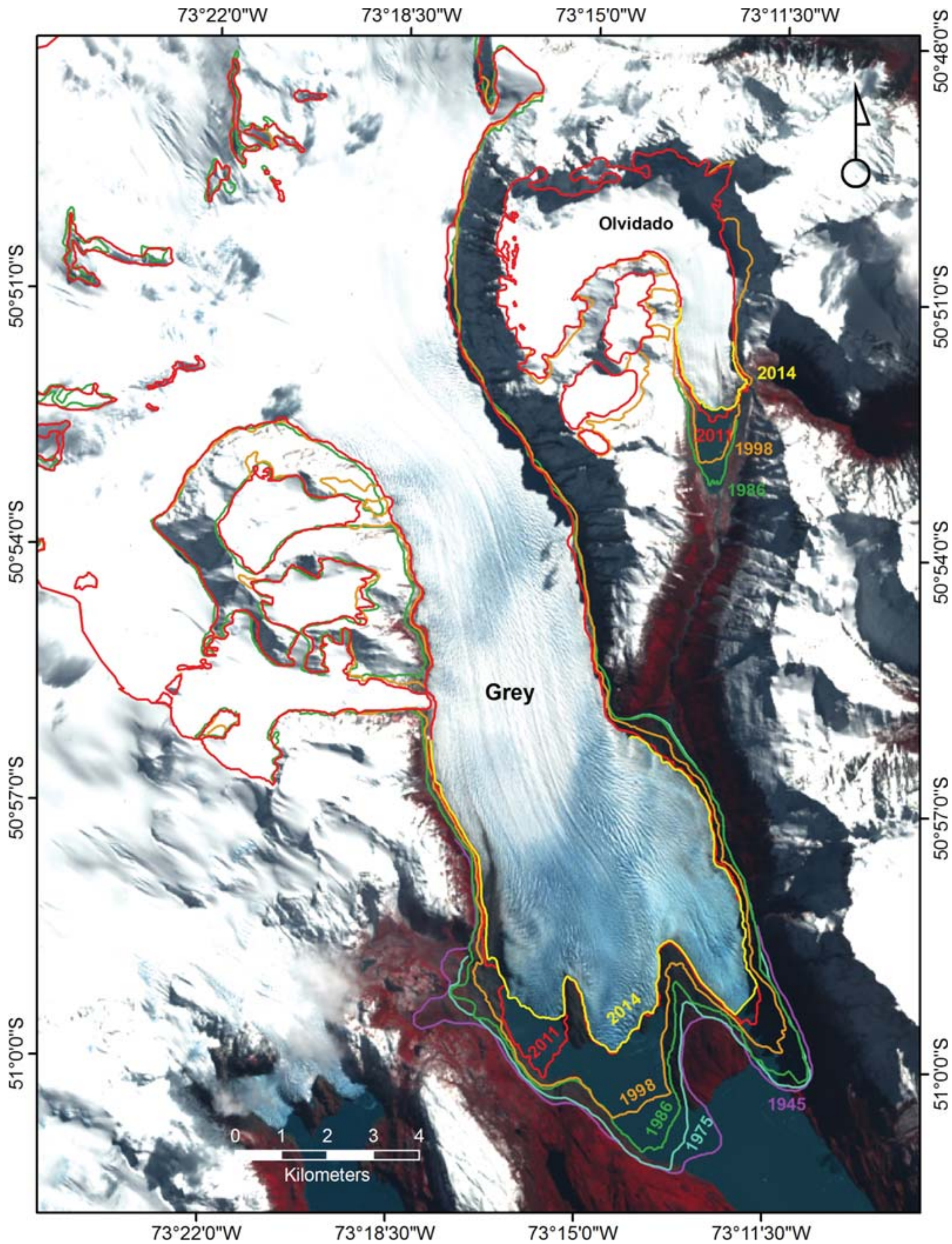

Figure 5 Grey and Olvidado glaciers (Torres del Paine National Park, Chile). Pre-1985 data from Rivera and Casassa 2004. Reproduced from Regents of the University of Colorado.

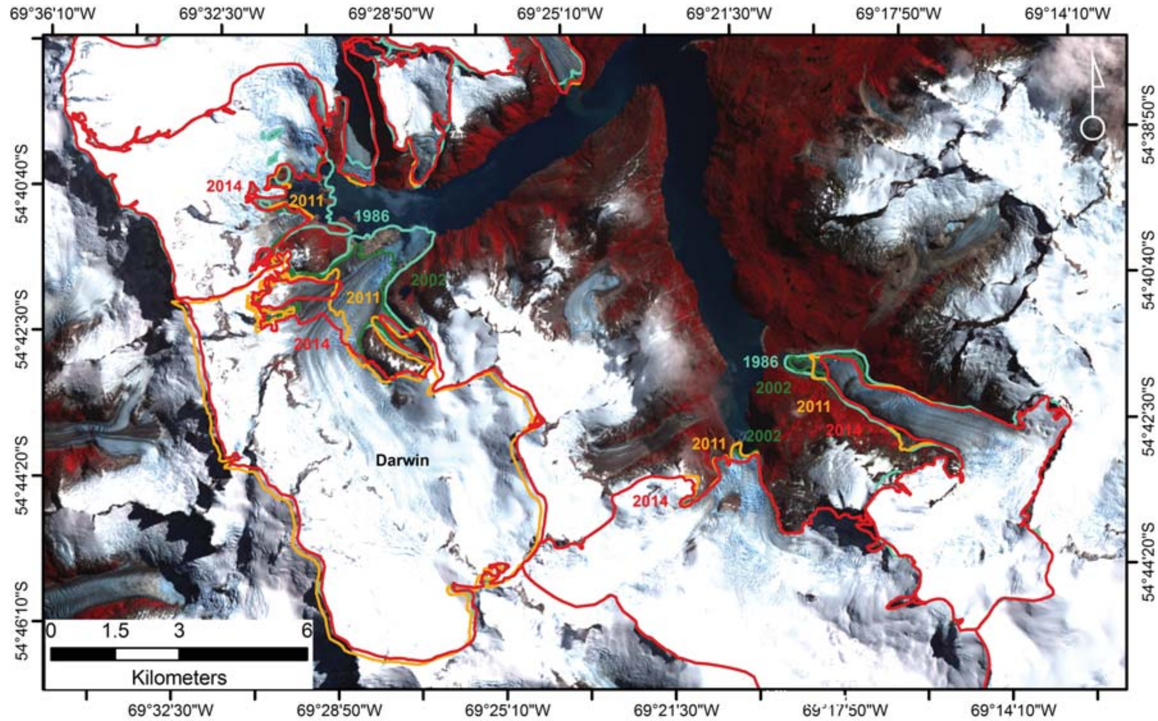

Figure 6 Glacier changes in Parry fjord, Cordillera Darwin, Isla de Tierra del Fuego (Chile).

3 km, 1985–2014). This particular frontal retreat is more likely related to the bathymetry of the fjord and is not necessarily fully connected with climatic changes. In total, the six glaciers studied here have lost 10% of their area since 1986.

Related climate change and glacier areal losses

When comparing all the glaciers studied in each zone (Figure 7), it became clear that there is a general trend of areal loss, and that the rate of loss has accelerated in recent years, especially in northern Chile. However, the largest individual percentage glacier area loss was observed in the Lake District, where the reduction trend does not show a significant variation since 1989. Overall, glacier area change rates (Table 1) show that in some zones, glaciers may disappear by the end of the twenty-first century if ongoing deglaciation continues without alteration. Conversely, glaciers in Patagonia will likely last for many more centuries, even in the worst scenario of climate change that will be discussed in the following section.

In the Chilean Andes, high-altitude climatic stations that are in close proximity to glaciers are sparse. One of the few stations with such characteristics is El Yeso (33°41'S/70°06'W, 2475 m asl) (Figure 1). Data from this station shows a clear warming trend since the 1960s (Figure 8), a trend that is also observed in Santiago (Quinta Normal at 527 m asl). However, this warming trend is highly dependent on the climate shift of the 1970s associated with the El Niño Southern

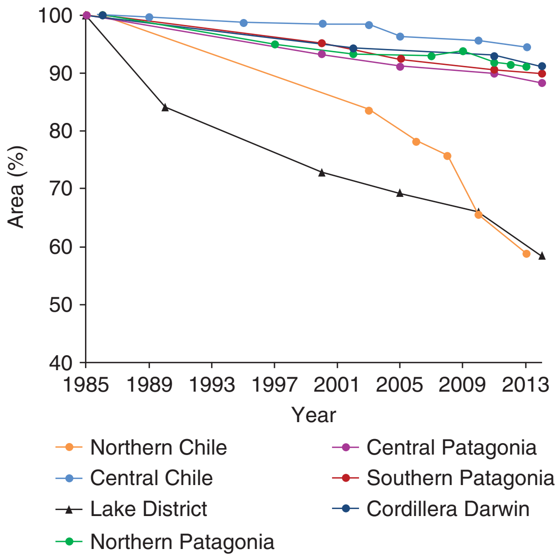

Figure 7 Glacier areal changes in selected regions.

Oscillation phenomenon (Falvey and Garreaud 2009). This long-term warming trend, at high altitude in the Andes where the glaciers are located, is forcing an upward migration of the regional snowline, effectively increasing ablation and reducing snow accumulation on glaciers (Carrasco, Casassa, and Quintana 2005).

Figure 9 shows a comparison between glacier areal losses for each glacier considered in this study and the temperature anomalies obtained from NCEP-NCAR reanalysis at the approximate altitude of the glaciers (Table 1). All these time series of temperature anomalies show that the climate shift of the mid-1970s, described above and below, exhibits contrasting behaviors.

The northern zone shows a clear trend of higher temperatures in the past 15 years, which could be triggering the strong upward migration of the snowline, reducing snow on the glaciers, which would explain the area shrinkage of the Maranceles and Tronquitos glaciers. The central zone shows very small temperature increases after 1970, as observed in El Yeso (Figure 8); consequently, a small glacier retreat is understandable for glaciers on the Marmolejo and San José volcanoes, illustrating the variety of glacier behaviors in this region. Further south, where the Tolhuaca volcano and Sierra Velluda glaciers are experiencing very high areal losses, there is no temperature trend in NCEP-NCAR reanalysis data (Figure 9). Since little volcanic activity has been observed in this zone, the glacier shrinkage must be related to precipitation reductions, as detected by Quintana and Aceituno (2012). Near Michinmahuida volcano, air temperatures have shown a moderate increase since the mid-1970s, and the areal reductions must be explained by precipitation changes and volcanic activity (Rivera and Bown 2013). In the rest of Patagonia, near the Northern and Southern Patagonian Ice Fields, the air temperature trends are clearly positive, especially in the past 10 years, this trend being the more likely triggering factor in the generalized negative areal changes.

Climate projections

For the twenty-first century, the IPCC (2013) indicates an increase in warming and a decrease in precipitation throughout Chile. The north of Chile (from 18°S to 30°S) appears to be the most affected zone in CMIP5 (Coupled Model Intercomparison Project Phase 5) models' mean composite for each scenario, with temperature anomalies in 2100 (with respect to 1986–2005 mean climate) from 1.2°C (rcp26) to 5.3°C (rcp85) (Figure 10). The projected temperature change for the central zone is estimated to range between 0.8°C and 3.4°C. Precipitation appears more consistent in all future scenarios, with reductions ranging from 5 to 10%, between 30°S and 43°S, without significant changes further south.

In all these future scenarios of climate changes, glacier retreats will continue, with glaciers especially affected in northern Chile, where

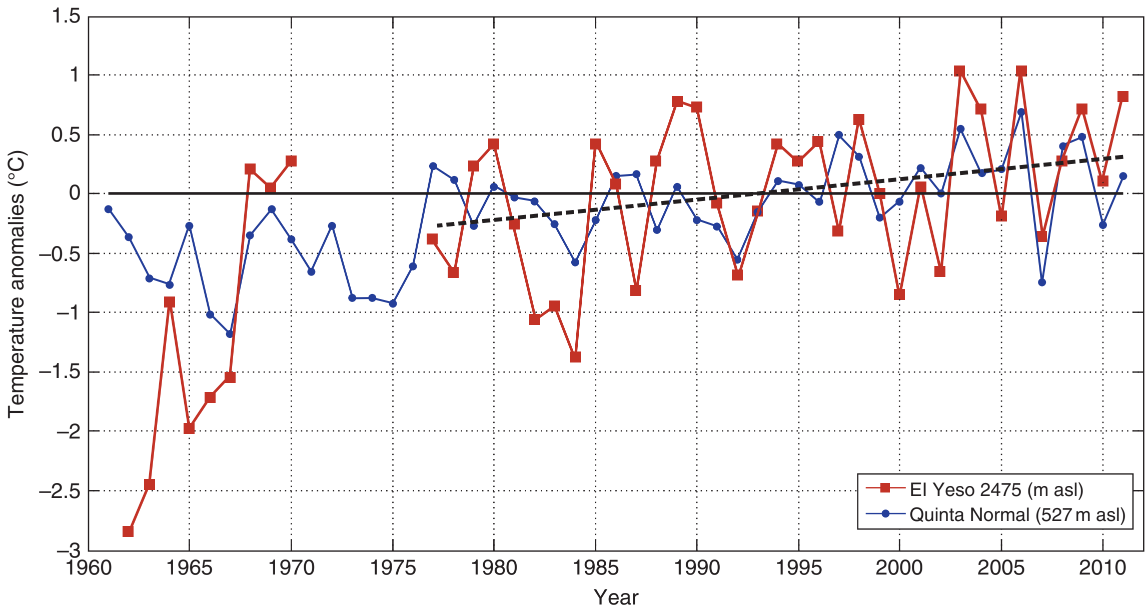

Figure 8 Air temperature changes in the Chilean central region.

small and low-altitude glaciers will very likely disappear by the end of this century. In central Chile, the glaciers will be increasingly affected, as long as end-of-summer snow lines (equilibrium line altitudes) keep rising (Carrasco, Quintana, and Casassa 2005). In the Lake District, the ongoing deglaciation will accelerate if the ongoing reduction in precipitation is not reversed. In Patagonia, temperature trends will certainly increase ablation, inducing high thinning and negative mass balances, as observed in the past decade.

Conclusions

The 41 selected glaciers included in this study, located along the Andes, including a wide variety of glacier types, are showing area reductions and negative frontal changes. This trend is not uniform among the selected glaciers, with the strongest changes taking place in northern Chile and in the Lake District. In central Chile, glaciers are also retreating but at lower rates than in northern Chile. In Patagonia, the changes are important in terms of total areas, but due to the huge amount of ice in this southern zone, areal loss percentages are much smaller. In this zone, there are also some anomalies, especially among calving glaciers, some of them exhibiting an enhanced retreat compared to noncalving glaciers, and in two cases there are advances. The changes detected in this work are representative of the area reductions taking place in other glaciers along the Chilean Andes, with some of them showing much stronger area shrinkages (some in connection with volcanic activity) and some exhibiting smaller area reductions (for example on the partially debris-covered glaciers). The main driving factor explaining these generally negative changes is certainly the observed atmospheric temperature changes, especially at high altitude in the Andes. However,

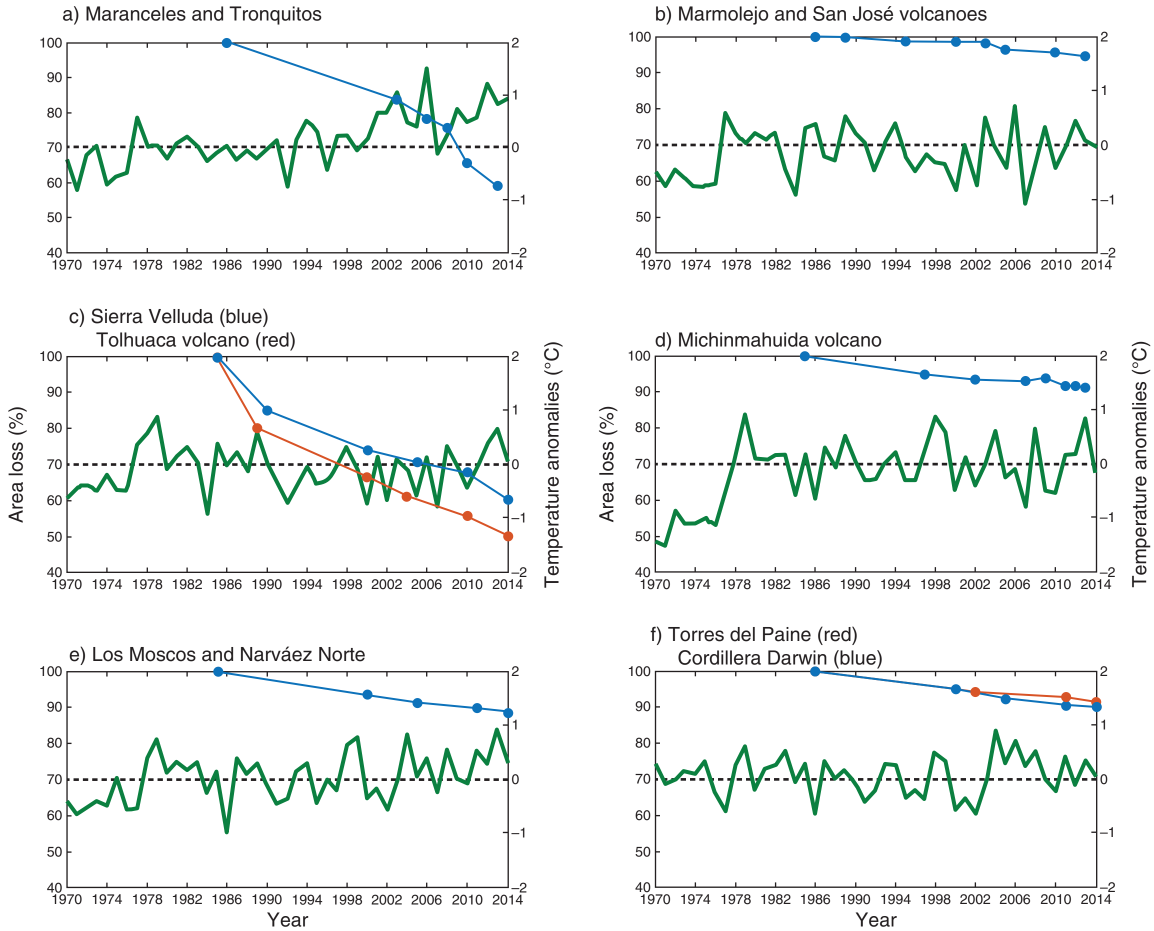

Figure 9 Glacier areal losses (blue and red lines) and air temperature anomalies (green lines) per glacier zone.

precipitation variability also plays an important role. All the scenarios of climate change for the rest of this century are indicating an increment in temperatures for almost the entire country, and a reduction of precipitation along the Andes between 30°S and 43°S. In these scenarios, glaciers will experience further reductions, with the smaller and lower-altitude glaciers probably disappearing by the end of the century. In central Chile and Patagonia, the ongoing changes will be enhanced, but the great number of large glaciers, the altitudinal ranges of these glaciers, and the amount of accumulation will certainly preclude their disappearance in the long term.

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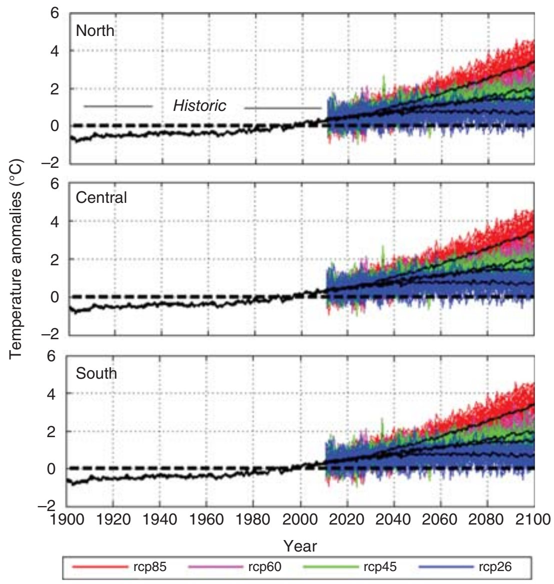

Figure 10 Future IPCC (2013) scenarios of temperature changes in Chile (rcp = representative concentration pathway).

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SEE ALSO: Cryosphere: remote sensing; Glacier changes; Glaciers; Intergovernmental Panel on Climate Change (IPCC)

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