Chapter 3

Climate Factors' Effects on Glacier Variations in the Commune of Alto del Carmen, Chile

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Additional information is available at the end of the chapter

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Abstract

Ice bodies in the semi-arid mountainous regions of Chile are of vital importance for the local population. As variations of their extent are often associated with climate change, this study focuses on the glaciers and glacierets situated in the Commune Alto del Carmen and local and regional climate. We combine statistically Landsat satellite imagery, historical and ongoing weather data. The present study covers a time span of 21 years, 1994–2015. Our results indicate that the extent of all ice bodies has continuously diminished as a consequence of long-term climate variability.

Keywords: Glaciers, Andes, Climate ENSO

1. Introduction

Since the end of the Little Ice Age, from about 1300 to about 1850, many worldwide glaciers have decreased in volume and extent [1]. Therefore, some of them at present are finished and others will disappear in the near future [2, 3]. It is understood, but still not very well documented, that glacier retreat is closely coupled to global climate change and anthropogenic interventions [4, 5, 6, 7]. This is mainly due to the complexity of weather system because of difficult climate history reconstruction. The main causes of receding glaciers, which can be attributed to climate variations, are constantly increasing global and regional temperature and lower stationary precipitation in the affected areas. Glaciologists have found out that the phenomenon of glacier retreat coincides with an increase in greenhouse gas emissions during and after the industrial revolution in the 18th century, see Figure 1. This means that human activities play a major role in this context. Even in a more direct way humans intervene, as exploration and exploitation of nature are activities that can be dated back till the beginning of the new age. It is quite clear that nowadays these interventions are carried out in a different way due to the possibility to use highly developed machines, and that the principal purpose has changed as in the past natural resources were exploited by humans as personal necessities had to be covered. At present, more economic reasons are in the foreground [8, 9, 10].

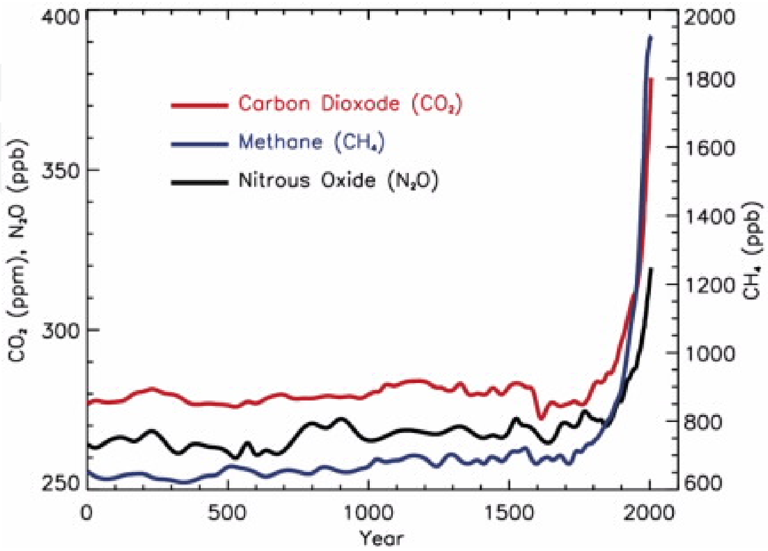

Figure 1. Trend of greenhouse gas emissions over the past 2,000 years (Source: [11])

Nevertheless, by all the interventions that are carried out by humans, ecosystems, our planet in general, suffer continuous alterations. But it would be simple to attribute every trend to humans as there are also natural circumstances, seasonal, periodic and single events, which affect nature. In any case, regardless of what or who have responsibility, the phenomenon of glacier retreat has to be studied as its impact is huge and might affect a whole region or even a country [12].

It has to be mentioned that glacier retreat should not be confused with other cyclical phenomena, like some melt during spring and summer months, which have almost no negative impact on glaciers. Annual thaw starts each spring in the mountains and causes melting of snow and ice accumulated during winter. The melting snow during spring and summer months causes an overall positive impact, since it generates a valuable source of fresh water. During winter months, snow fall results in a recuperation of melted snow. In consequence, an almost neutral mass balance between warm and cold periods is achieved by nature as this process repeats year after year. This is not the case if glaciers melt as there is a negative mass balance during a certain period of time. So the problem arises when the phenomenon is not seasonal, the glacier does not recover its initial volume in the cold months, year after year, so its volume and extend gets diminished and in consequence, natural fresh water source for human consumption and irritation is threatened [13].

In South America, a total surface of about 26,000 km^2 is covered by glaciers. Almost 77% of this area can be found in Chile [14]; considering 1,751 glaciers (16,893 sqkm) already mapped and 5,000 sqkm estimated of not yet registered glaciers. Their distribution from north to south can be grouped as it is shown in Table 1.

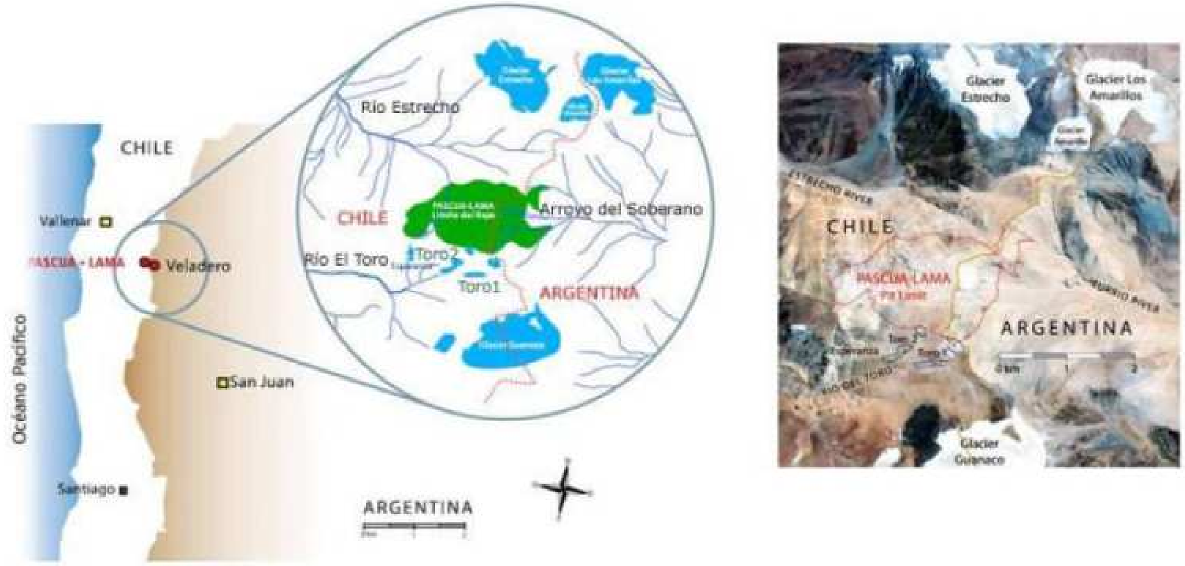

Figure 2. Glaciers and glacierets located in the study area

Natural Region	Region	Number of Glaciers	Surface [sqkm]
Far North	XV, I, II	28	42
Near North	III – IV	60	107
Central	V – VII, RM	1500	1019
South	IX, XIV, X	87	265
Far South	XI – XII	76	15460

Table 1. Geographical distribution of Glaciers in Chile

The current state of Chilean glaciers, according to [14] and [15], indicates that 87% is in decline, 6% in advance and 7% still remains unchanged.

Nowadays and in a near future, the water scarcity is a major concern all over the world. Especially in the arid to semi-arid mountainous regions, the local population hugely depends on alternative water resources such as those stored in glaciers or snow. Glaciological processes at high altitudes in such regions of Chile and Argentina (27°S to 33°S) have previously been studied with special focus on hydrology (e.g. [17]) and climatology (e.g. [17, 18]).

In the rivers that originate in the central Andes, the main water supply is generated from the snowfall that normally covers the upper mountain peaks each winter. Furthermore, besides these melting processes, surface runoff gradually flows into the rivers. During wet years, this runoff can deliver sufficient amount of water throughout the spring and summer period to compensate missing precipitation. In dry years, however, it tends to decrease towards the end of summer. In these drier periods, ice bodies have to provide enough melt water due to its natural resources accumulated in winter. The water contribution of glaciers, glacierets and other ice bodies is directly proportional to their area, as it is on the surface where melting caused by solar radiation, ambient heat and other environmental factors happens. As an example, the Chilean General Water Directorate (DGA – Dirección General de Aguas) estimates that the average, annual melting during summer fluctuates between 0.5 liters per second (l/s) per hectare and 1.8 l/s per hectare. The total area of the three glacierets located at the southern end of the study area was 16.5 hectares in March 2005, so that the total flow contributing to the basin was estimated to range from 8 l/s to 30 l/s during maximum of the melting period. In comparison, the average flow of Huasco River in Algodones, more westerly in an agricultural zone, is greater than 4000 l/s in summer.

In the Chilean Commune Alto del Carman, in the Atacama region, Figure 2, several glaciers can be found that have shown important variations during the past few decades. These glaciers namely are: Toro 1, Toro 2, Esperanza, Guanaco, Estrecho, Amarillo and Los Amarillos. Several other studies on glacier variations induced by climate have already been carried out in the past at different study sites, but in the vicinity of the mentioned glaciers. Ref. [19] studied the terminus of the Agua Negra Glacier (Argentine); [20] the Tronquitos glacier; [21] Cerro Topado; [22] the Huasco catchment. In 2003, [23] started a glacier and glaceriets (very small glaciers or ice masses of indefinite shapes in hollows and that have little or no movements; [24]) monitoring program in the region where all of the above mentioned glaciers are located.

1.1. Remote sensing of glaciers

Nowadays, traditional ground-based glacier monitoring studies can be complemented or even replaced by satellite-based data. Reflected solar radiation by the earth's surface is detected by optical, passive sensors in the visible (400–700 nm), near and short-wave infrared (700 nm – 7 μm) bands of the electromagnetic spectrum. Radiation emitted by the surface is detected by sensors in the thermal infrared (7 μm – 1 mm) bands. Electromagnetic radiation in the microwave bands (1 mm – 1 m) in remote sensing is used mostly by so-called synthetic aperture radar (SAR) active and passive systems [25].

Glacier monitoring can focus on several parameters such as glacier area and length, surface elevation, surface flow fields, accumulation and ablation rates or albedo. For mass balance study, in particular equilibrium line altitude (ELA), accumulation area ratio (AAR) and the mass balance gradient $\delta b/\delta z$ are of importance [26].

All these parameters are relevant to study the influence of glaciers on the environment [27]. Important fields are:

- Glacier Geology: Bedrock material removed by glaciers is redistributed in the landscape. Erosion and deposition caused by glaciers forms U-shaped valleys, cirques, moraines and other glacial landforms. Glacial sediment is redistributed by wind or water, forming new soils and affecting the water quality of rivers, lakes and oceans.

- Glacier Hydrology: Glaciers store water during cool, wet winter periods and release it during warm, dry summer.

- Glacier Ecology: Glaciers are habitats for flora and fauna. Their meltwater provides aquatic habitat for endangered species.
- Glacier Hazards: Significant hazards are outburst floods, lahars, ice avalanches and spontaneous landslides.

Considering these two principal aspects, sensor types and glacier characteristics, one has to decide what kind of data has to be generated and which method is the most appropriate [28]. For example, digital elevation models are a key element for glacier volume change studies. Several conclusions can be drawn out of it, such as mass balance variability due to climate change. Furthermore, glacier surface flow velocity can be derived from differential InSAR observations and/or feature tracking in optical satellite images.

In scientific literature, a lot of examples can be reviewed that highlight the potential of remote sensing for glaciologic studies carried out all over the world, such as those in Alaska [29], Patagonia [30], the Andes [31], the Alps [32], the Himalaya [33] and Central Asia [34].

Table 2 gives an overview of most common satellites and their application in glacier monitoring.

Satellite	Operation dates	Bands	Glaciological application
Landsat	Series of satellites since 1972	VIS, IR	Glacier variations, spectral characteristics of snow and ice
SPOT	Series of satellites since 1986	VIS, IR	Glacier variations, spectral characteristics of snow and ice
SENTINEL	Series of satellites since 2014	VIS, IR, MW	Glacier variations, spectral characteristics of snow and ice, elevation change monitoring
CRYOSAT-2	Single mission since 2010	MW	Glacier variations, surface velocity estimation, elevation change monitoring
TERRA	Single mission since 2000	VIS, IR, MW	Glacier variations, elevation change monitoring

Table 2. Satellites and their possible application in glacier monitoring

2. Climate

Inter-annual global climate variability is mostly caused by the coupled ocean–atmosphere phenomenon ENSO (El Niño Southern Oscillation). It is a naturally, irregularly occurring phenomenon that is characterised by fluctuating ocean temperatures in the equatorial Pacific, between Australia and the west coast of South America. El Niño refers to a warming phase whereas La Niña refers to a cooling phase of the Pacific sea surface temperature (SST), the upper layer (0–10 cm) of the ocean. As ENSO is a coupled ocean–atmosphere phenomenon, air surface pressure in the tropical Western Pacific is higher than normal in case of El Niño and lower in case of La Niña. Both in general last several months or even years and vary in intensity.

ENSO has particular impact on inter-annual climate variability in Latin and South America. In Mexico and parts of the Caribbean, El Niño causes an augmentation in winter precipitation and a diminution in summer precipitation [35]. Severe droughts in Mexico have occurred during summer when El Niño was present [36]. La Niña, however, has an almost opposite effect, precipitation increases during summer months and decreases in winter.

In case of Colombia, El Niño causes reductions in precipitation, whereas La Niña is associated with stronger precipitation, which might result in floods [37]. Furthermore, they indicate that there exists a very high positive correlation between the Southern Oscillation Index (SOI) and river discharge in Colombia. During the December–January period, this relationship is stronger and weaker during April and May. There is also a regional difference. In western Colombia the influence of El Niño is stronger than in the east.

Large positive precipitation anomalies over the eastern part of the Andes (Ecuador and northern Peru) typically are observed during the warm episode [38].

In the Amazon region of Brazil northward to the Caribbean, deficiency in precipitation has been observed during El Niño [39]. In contrast, El Niño effects in southern Brazil are opposite to that in northeast Brazil and northern Amazonia. Positive and extremely large anomalies of rainfall have been observed during El Niño years [40, 41].

Between 30°S and 40°S, northern and central Chile and at high altitudes of the Andes in Argentina, most precipitation is recorded during winter months, with positive anomalies, which can be registered during early stages of El Niño. Due to the area's semi-arid conditions, local and regional economy might strongly be affected [42, 43, 44]. These events stand in contrast to what happens at low altitudes of Chile. Between 1991 and 1993, El Niño years, heavy rainfall triggered debris flows in Santiago de Chile, Antofagasta and surrounding areas [45].

At high altitudes of the Andes, large amounts of snow are consistently recorded. During summer, melting of accumulated snow is the main cause of river runoff. In Chile and central-western Argentina, north of 40°S, during El Niño years, streamflows were normal or above normal [46, 47]. In contrast, during La Niña years, negative anomalies of rainfall and snowfall can be observed with opposite consequences, which include below-normal summer streamflow. For this region, it is more probable that dry conditions occur during La Niña than wet conditions happen during El Niño years [42].

SST observations and analysis are often used to identify this oscillation and to predict the upcoming climate variability. Nevertheless, it has to be mentioned that it is the sub-surface ocean temperature, which indicates first an upcoming change, a transition from a cold to a warm phase or vice versa. It is important to understand that changes in sub-surface ocean temperatures are the first to respond to an oncoming change in the ENSO phase.

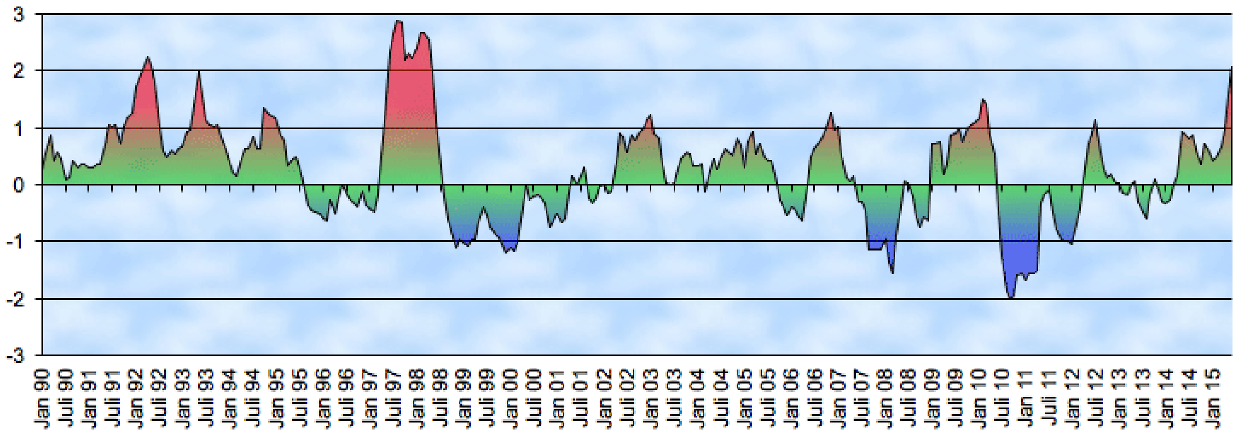

Figure 3. Multivariate ENSO Index (MEI) since 1990 (Source: [48])

Nevertheless, to monitor ENSO in literature the Multivariate ENSO Index (MEI), Figure 3, which is based on the six main observed variables over the tropical Pacific, can be found. These six variables are: sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature and total cloudiness fraction of the sky. At first, the MEI is computed separately for two consecutive months (Dec/Jan, Jan/Feb,...). Then, spatially filtering of the individual fields into clusters is applied [49]. The MEI is calculated afterwards as the first unrotated principal component (PC) of all six observed fields combined. Finally, the first PC on the co-variance matrix of the combined fields is extracted [50]. In Figure 4, the results of the past 25 years are illustrated. Positive values (in red) indicate El Niño phases whereas negative values (in blue) represent La Niña phases.

2.1. Remote sensing of climate

Since 1959 when the first space-borne observations of solar irradiance and cloud reflectance were made by the Vanguard-2 satellite, remote sensing gradually became a key observation and research method in climate change studies [51]. Satellite data of land, ocean and atmosphere are used to model and simulate the dynamics climate system in the past, present and future [52, 53].

Although satellite remote sensing, on a climate history time scale, is a relatively new technique, and therefore has some limitations such as short data spans of satellite records, biases associated with instruments and uncertainties in retrieval algorithms, it has to be considered in a series of particular applications that are listed in Table 3.

Application	Observation	Satellites
Global warming	Global temperature trends, particularly at the ocean surface and in the atmosphere.	NOAA, AQUA, TERRA
Snow and ice	Monitoring the dynamics of snow extent and ice covers	NOAA, SSM/I, ERS
Sea level change	Mapping of ocean surface topography	TOPEX/Poseidon, GRACE, Sentinel
Solar radiation	Determination of changes in the sun's luminosity	SORCE, Meteosat, Eumetsat
Aerosols	Atmospheric particles concentration	TERRA, AQUA
Water vapour and precipitaion	Precipitable water in the troposphere; spatial and temporal variability of precipitation at global scale	TERRA, AQUA
Clouds	Estimation of net cloud forcing	Cloudsat, TERRA, AQUA

Table 3. Remote sensing in climate change studies

3. Objectives and study area

The main objective of the present work was to determine surface area changes of glaciers in the Commune of Alto del Carmen (Chile) in the near north during the past two decades. And the specific goal of the study was to link these changes to climate variability in the study area.

Our study focuses on the following glaciers and glacierets located in the Commune of Alto del Carmen: Toro 1, Toro 2, Esperanza (all defined as glacierets) Guanaco, Estrecho, Amarillo and Los Amarillos (all defined as glaciers), see Figure 2. Ref. [22] found out that their spatial distribution is highly correlated with natural factors, such as terrain characteristics, solar radiation and shadowing effects. Ref. [54] indicates that only little ice flow exists and that surface areas are smaller than 2 sqkm in 2007. Furthermore, they mention, based on ground penetration radar (GPR) measurements, that ice thickness can reach up to 100 meters. More historical studies of area changes [23] have shown that during the past 50 years, surface area has reduced significantly in almost all glaciers and glacierets.

Furthermore, it is noteworthy that an important mining project of gold, silver, copper and minerals is developed in the nearby vicinity. At first, the responsible mining company (Barrick Gold) proposed to move Toro 1, Toro 2 and Esperanza glacier, as they were considered of little relevance to the basin water, are located in the pit area of the foreseen mine and were in process of disappearance (observed high melt rates). National and Regional Environmental commissions (CONAMA and COREMA, respectively) approved the mining project in general. Nevertheless, they made a couple of observations to the initial proposal and prohibited to move glaciers. As a consequence to the already carried out exploitation activities, such as drilling, and installation of infrastructure, e.g. access roads, several negative effects can already be observed.

- Watershed: There are two rivers, which are directly affected by the Pascua Lama mining project, as their source is in that area and are fed by melting snow that infiltrates the ground: On the Argentinian side, it is river Turbio and on the Chilean side, it is El Estrecho river. On its way through rocks and materials that make up the upper river sources, the water comes into contact with the minerals in the soils of the Pascua-Lama deposit. Due to its chemical and mineralogical composition, water becomes acid and can dissolve metals contained in the rocks.
- Glacier: In 2001, COREMA approved the so-called Environmental Impact Assessment of the Pascua Lama Project, which was presented by Barrick Gold. In this study report, several environmental impacts were outlined. Furthermore, several mitigation measures and monitoring programs were proposed to protect the environment. The assessment covered those environmental components, which were considered as most relevant, including: air quality; levels of noise and vibration; flow and quality of surface and groundwater; geomorphology, drainage and soil; vegetation and flora; terrestrial fauna; aquatic flora and fauna; landscape; cultural heritage; road service levels; and socio economy. Nevertheless, glaciers were not considered to be protected. It was proposed to move them to a different location. As this was never realized, the mining company constructed a transportation road right through one of them.

4. Methodology and data

Glacier and glacieret surface area were determined from georeferenced satellite images acquired by Landsat 5, 7 and 8. These satellite images were acquired during summer months from 1994 until present, for two reasons: (1) Cloud cover in the satellite images had to be less than 10% and (2) glaciers can be detected very easily and with high certainty as seasonal snow cover does not exist anymore. Their ground sampling distance (GSD) is 30 m in all spectral bands. Landsat 7 satellite images with SLC (Scan Line Correction) off had to be re-processed to fill gaps. This was done by spectral interpolation for every affected satellite image.

Satellite	Time Span	Total Number of images
Landsat 5	1994-2003	10
Landsat 7	2004-2013	10
Landsat 8	2014-2015	2

Table 4. Satellite images used in this study

With all the satellite images acquired, corrected and georeferenced, at first, a visual identification, interpretation and analysis of the glaciers and glacierets were carried out to detect inter-annual variations. In a second processing step, image digitalization was applied with the aim to measure glacier extent and to derive surface area variations.

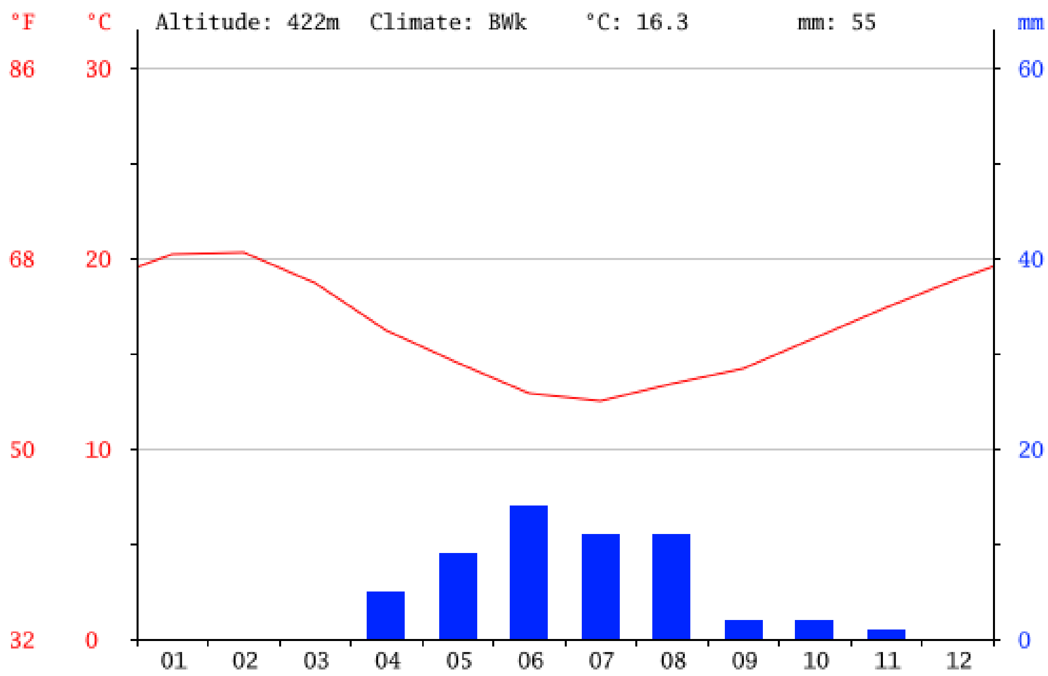

Figure 4. Climate chart for the city of Vallenar

Climate data, which is relevant for this study, is available for free on the internet. There are several weather stations situated in the Atacama region close to the study area. The most complete data set of precipitation and temperature records is available for the city of Vallenar, located at 100 km to the northwest of the study area. Furthermore, climate data registered for the cities of Conay (60 km to the north) and Chollay (50 km to the northwest) are available, but only from 2008 onwards and with some gaps. Therefore, measurements until 2008 at a fourth station, namely La Olla (80km to the southwest), are taken into account. This data was taken from [23].

In a final step, Pearson product–moment correlation between climate and digitised data is generated. Both are linked together with a special focus on anomalies and unusual events, e.g. high temperature events, heavy and prolonged rainfall. The statistical correlation is determined by the relationship or dependence between the two studied variables: area (sqkm), temperature (T °), precipitation (mm), in a two-dimensional distribution. In case that there can be found one of these variables influencing another, it can be stated that the variables are correlated or that there exists correlation between them.

The linear correlation coefficient is calculated as follows:

$$r = r_{xy} / r_x r_y \ ; r \ \varepsilon \left[-1,1 \right]$$

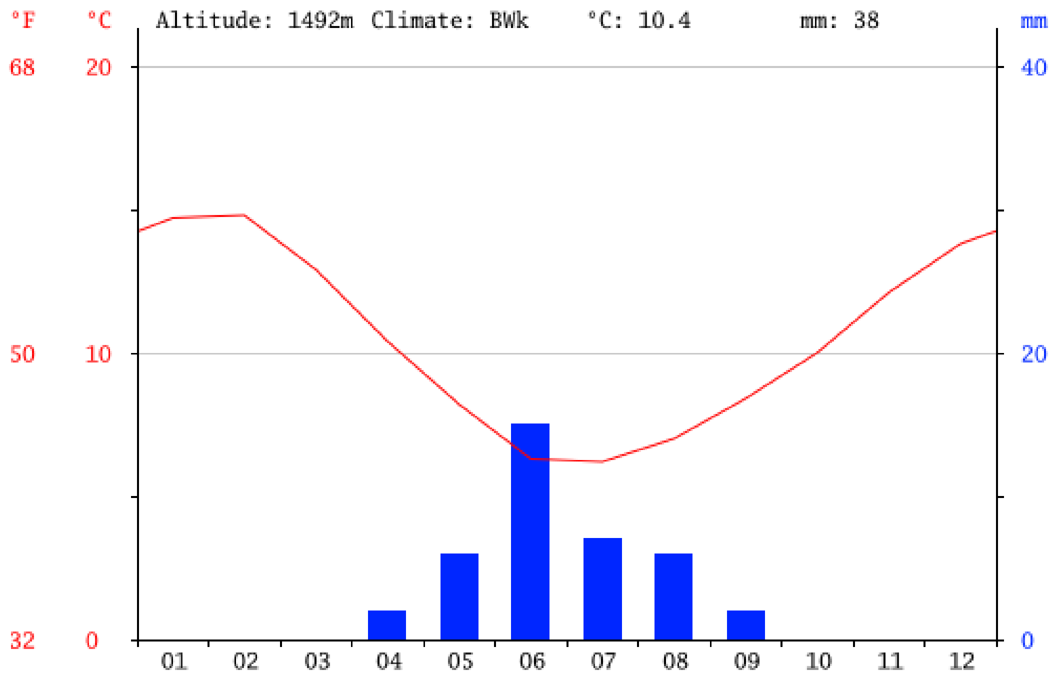

Figure 5. Climate chart for the city of Chollay

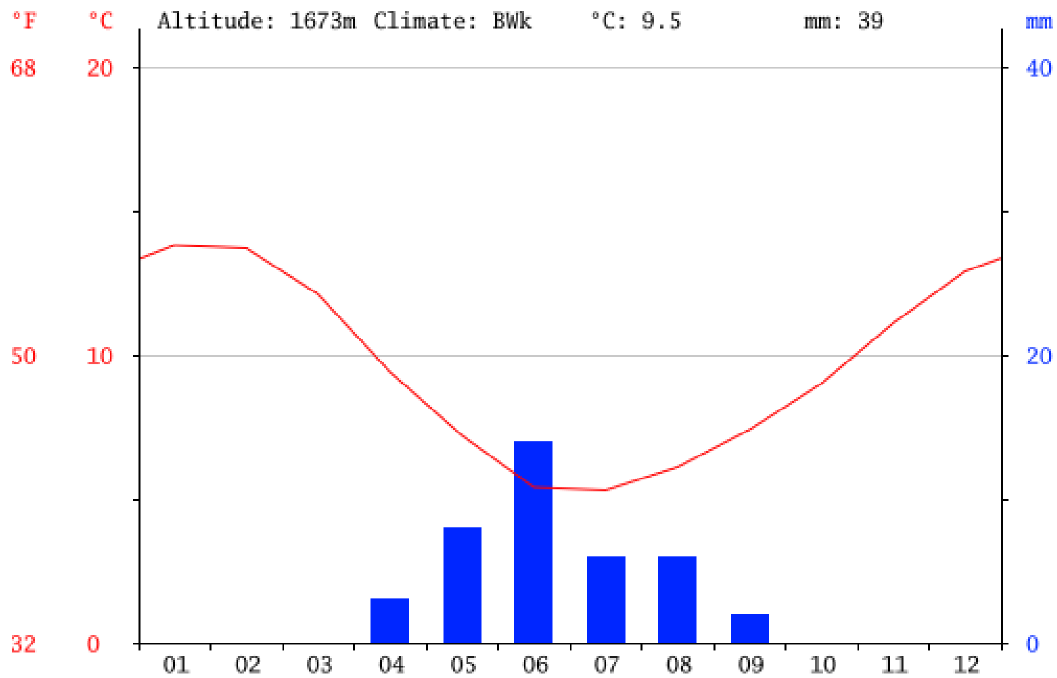

Figure 6. Climate chart for the city of Conay

where r_{xy} is the xy covariance, r_x and r_y are the standard deviations, respectively.

ϱ can vary between –1 and 1. In case that the correlation coefficient is 1, there is a perfect increasing linear correlation; if it is –1, a perfect decreasing linear relationship can be found between the variables; in all other cases, the value indicates to which degree a linear dependency exists. So, a 0 value means that no correlation exists between two analysed parameters.

For our study, this can be interpreted the following way:

	$r_{surface,\ temperature}$	$r_{surface,\ precipitation}$
Positive	Glacier surface area decrease (increase) due to temperature decrease (increase)	Glacier surface area decrease (increase) due to precipitation decrease (increase)
Zero	No correlation between glacier surface area and temperature variations	No correlation between glacier surface area and temperature variations
Negative	Glacier surface área decrease (increase) due to temperature increase (decrease)	Glacier surface área decrease (increase) due to precipitation increase (decrease)

Table 5. Possible results of correlation coefficients statistics and their interpretation regarding surface

5. Results and discussion

The Figures 7–13 show how surface area of the studied glaciers and glacierets has reduced during the past 25 years. The blue line indicates the glacier extent in 1994, whereas the green line delimitates the glacier area which was observed in the last suitable satellite image. The surface area which was lost during the past two decades is highlighted by linear hatching in red colour.

In case of Los Amarillos glacier (Figure 7), surface area difference between 1994 and 2015 is –43.53%. More area loss can be identified in the southeastern part of the glacier.

Amarillo glacier (Figure 8), during the past 20 years, has diminished 62.12%. In particular, the southern extend of the glacier has significantly reduced.

Figure 9, which shows the surface area loss at Estrecho glacier, indicates that it has lost surface area almost uniformly; no specific spatial trend can be identified. All margins have uniformly reduced by means of extend. Surface area loss was 43.45%.

For Guanaco glacier (Figure 10), a similar behaviour as for Estrecho glacier can be identified, except the most westerly area, which has completely gone. In 1994, it was already isolated and only connected to the main glacier area by an ice bridge. Total surface area loss during the past 2 decades was 33.84%.

Toro 1 and Toro 2 (Figures 11 and 12) have shown similar spatial behaviours. The eastern part of both glacierets is gone. Only about 4% of the original surface area remains.

In Esperanza glacier (Figure 13), whose spatial extend was from north to south, surface area loss happened mostly in this spatial direction. Nowadays, the geometry of this glacieret is almost circular.

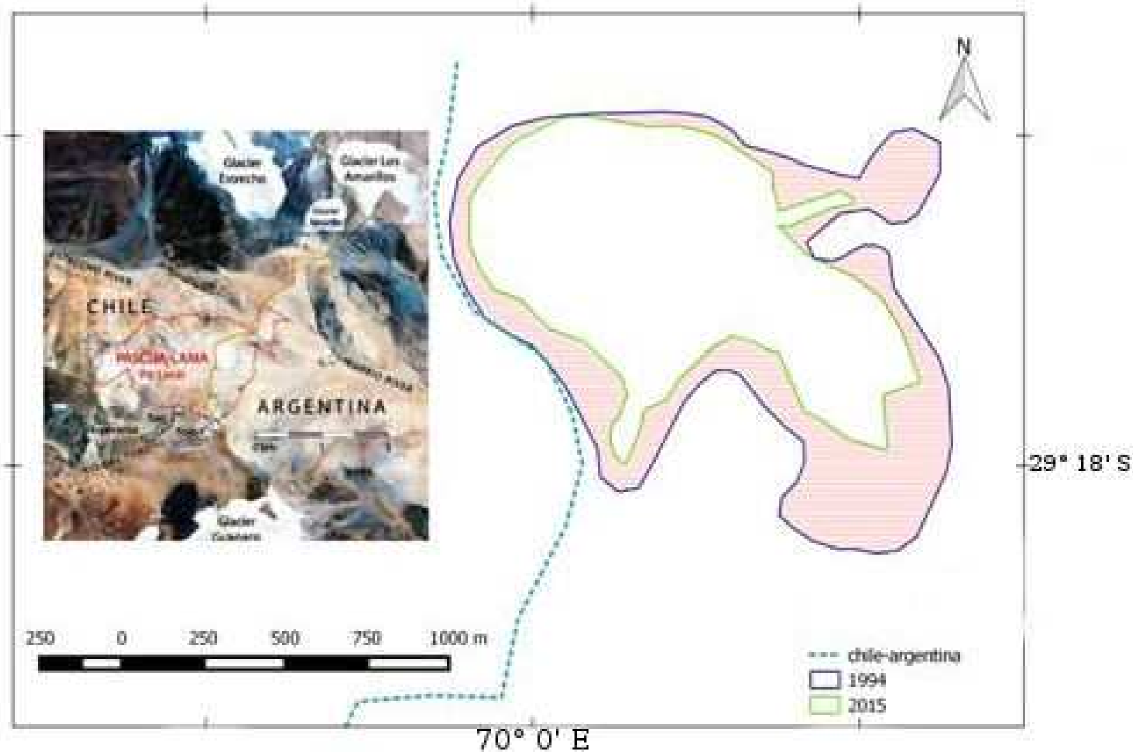

Figure 7. Surface area change of glacier Los Amarillos

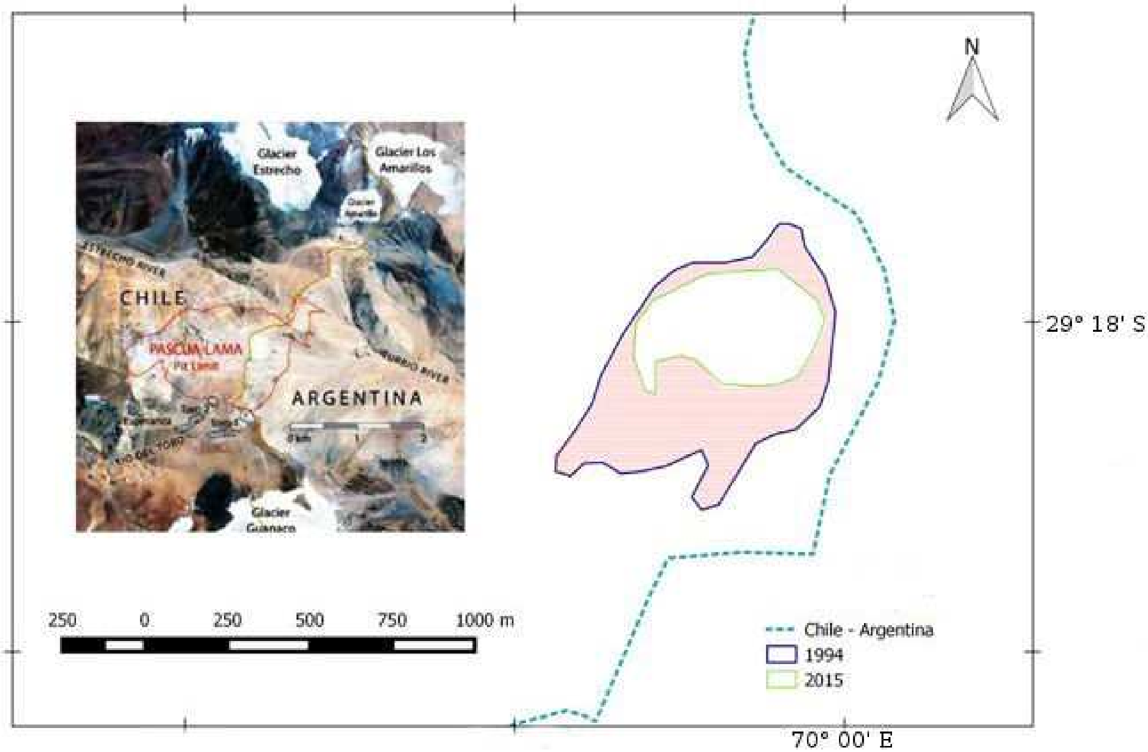

Figure 8. Surface area change of glacier Amarillo

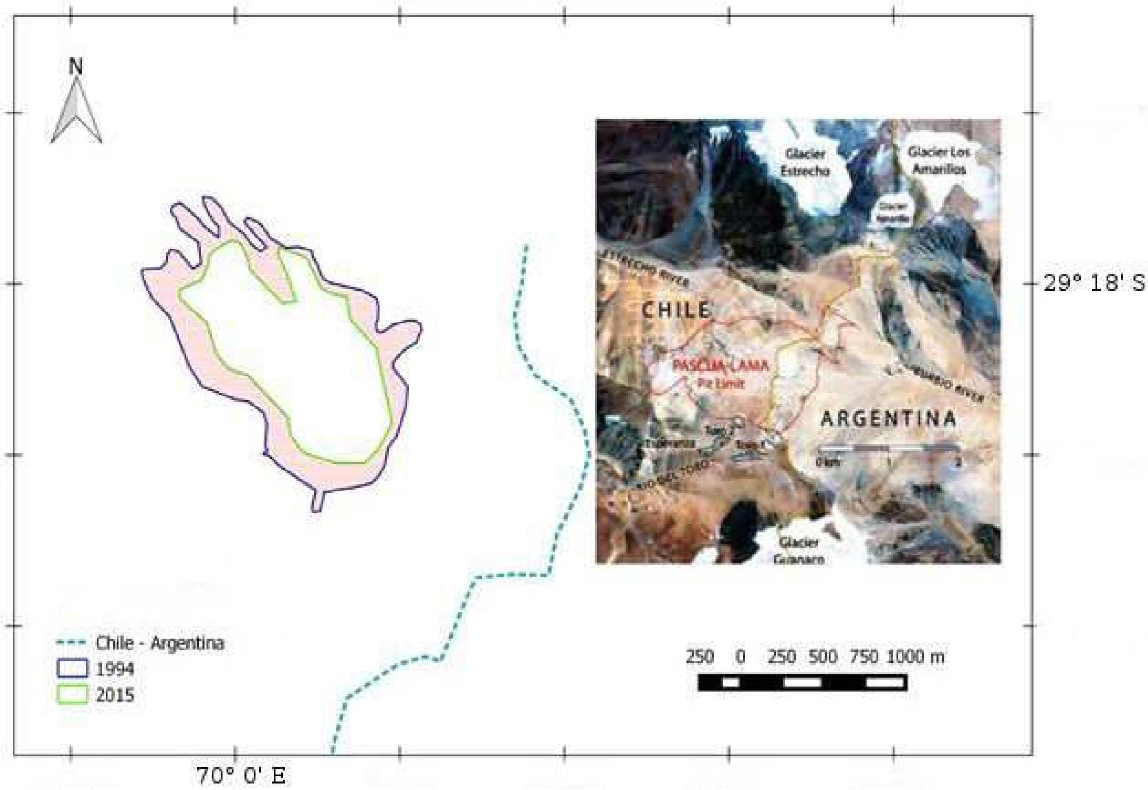

Figure 9. Surface area change of glacier Estrecho

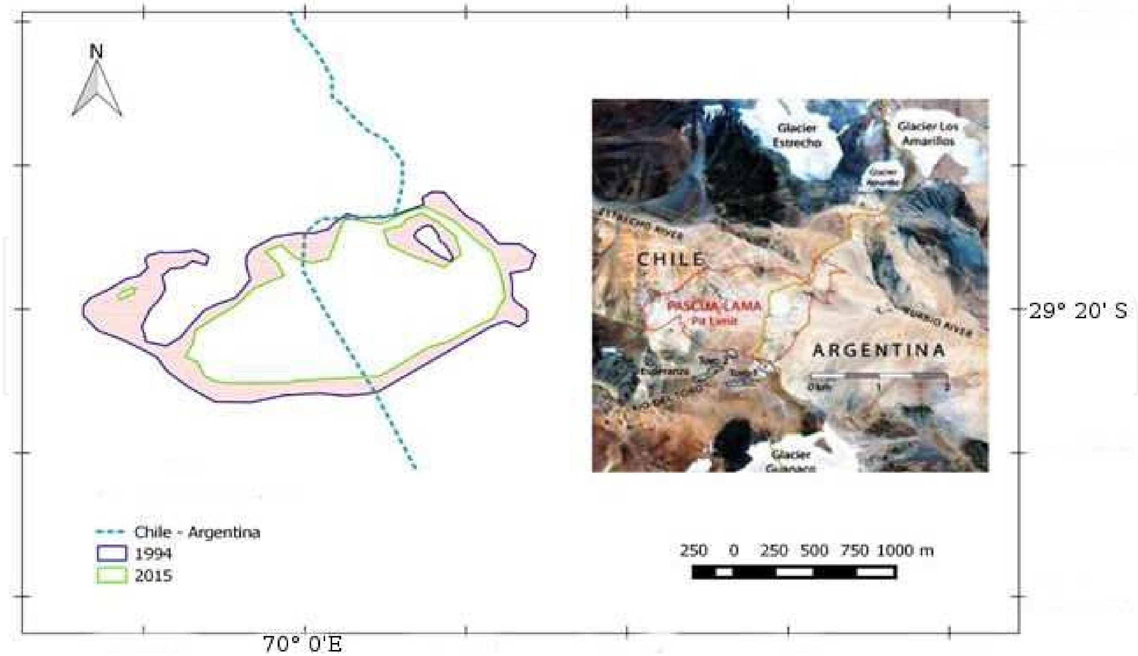

Figure 10. Surface area change of glacier Guanaco

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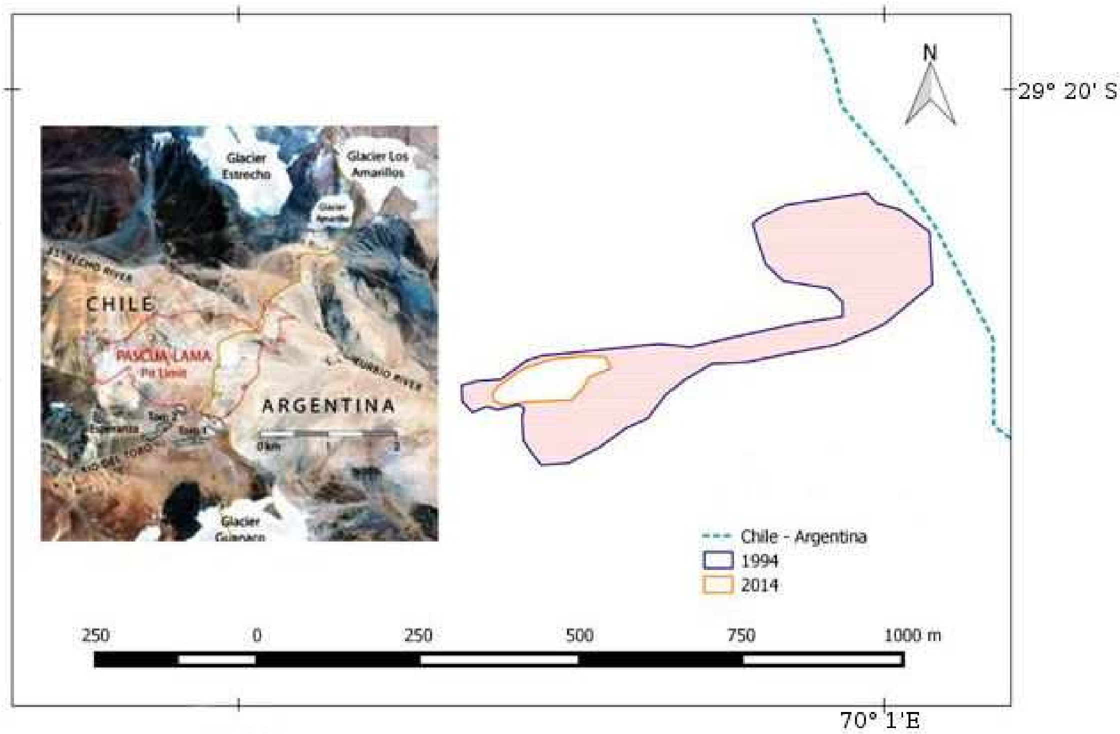

Figure 11. Surface area change of glacieret Toro 1

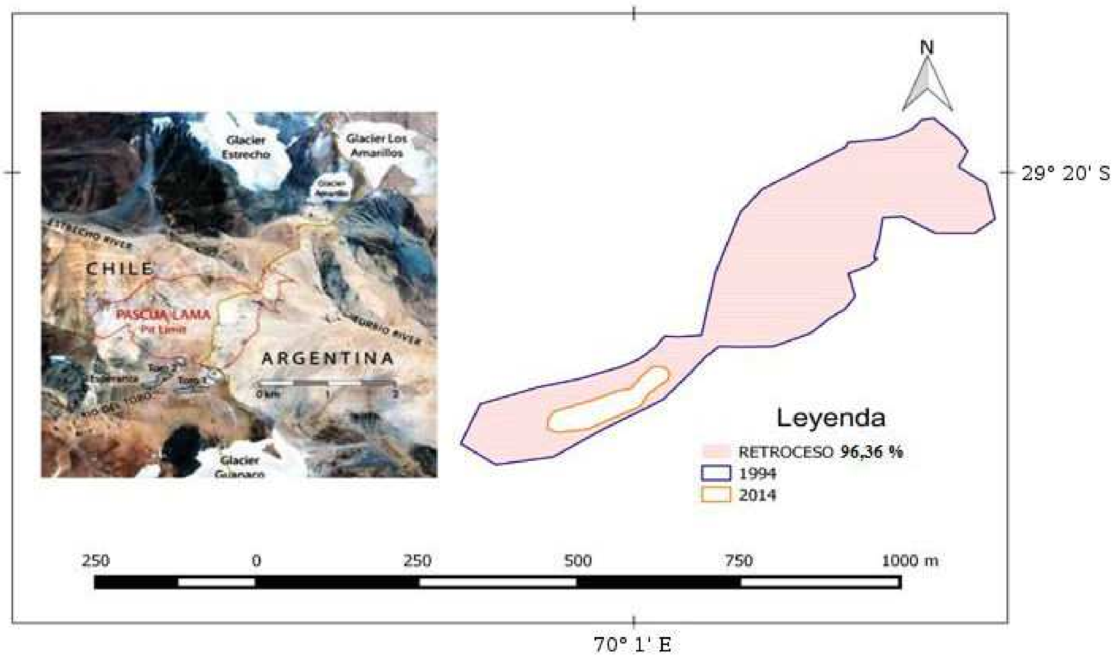

Figure 12. Surface area change of glacieret Toro 2

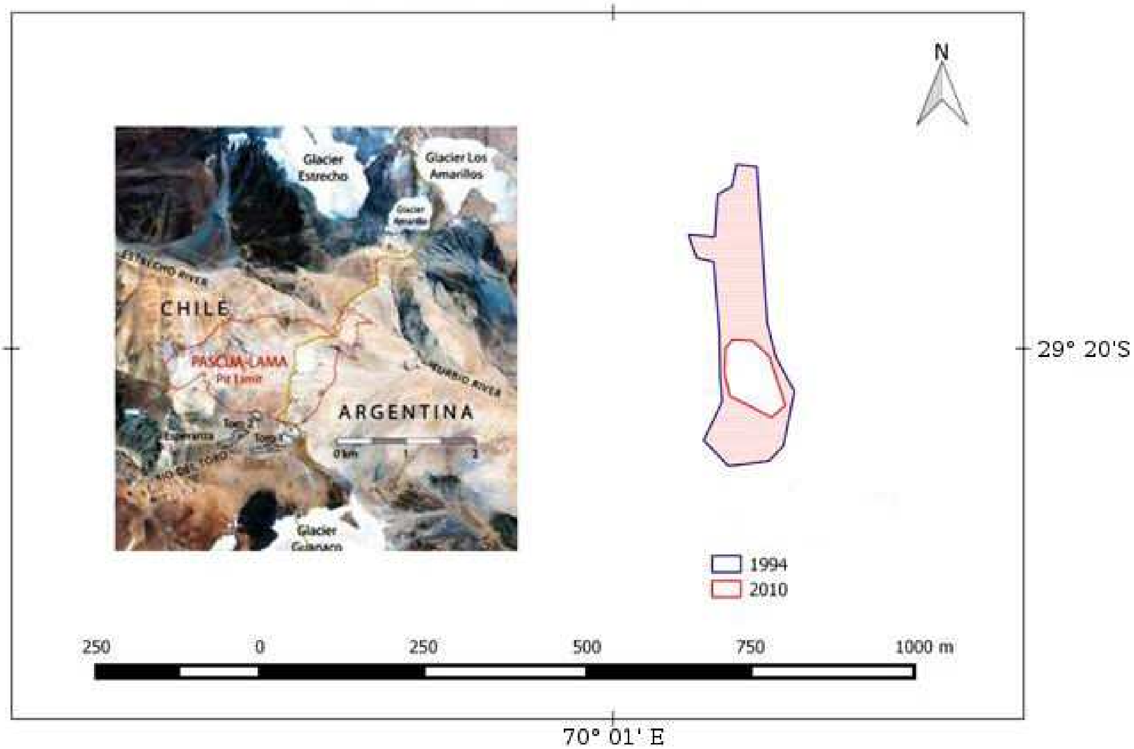

Figure 13. Surface area change of glacieret Esperanza

Table 6 shows the results of the digitalisation carried out to determine surface area variations. Only summer months were considered and satellite images of every second year were taken into account. The generated graphs show that all glaciers and glacierets have suffered surface area loss during the past 21 years. Nevertheless, some of them were able to recover during 2004, 2006 and/or 2008.

	1994	1996	1998	2000	2002	2004	2006	2008	2010	2012	2014	2015
Los Amarillos	1,291	1,104	1,293	1,296	1,149	1,263	1,031	1,274	0,855	0,796	0,852	0,729
Amarillo	0,378	0,376	0,491	0,379	0,331	0,317	0,334	0,278	0,168	0,134	0,173	0,143
Estrecho	1,459	1,865	1,366	1,311	1,081	1,356	1,439	1,350	1,117	0,954	0,986	0,825
Guanaco	2,077	2,254	2,181	2,038	1,999	1,942	1,720	1,893	1,668	1,479	1,482	1,374
Toro 1	0,163	0,137	0,233	0,101	0,059	0,063	0,090	0,084	0,019	0,000	0,008	0,000
Toro 2	0,199	0,124	0,364	0,044	0,022	0,060	0,089	0,113	0,000	0,000	0,007	0,000
Esperanza	0,036	0,015	0,106	0,009	0,025	0,018	0,079	0,043	0,009	0,000	0,056	0,034

Table 6. Absolute surface area values in sqkm from 1994 till 2015

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Toro 1, Toro 2 and Esperanza have not been gone. Here, zero values indicate that it was not possible to detect them in the satellite images of the corresponding years due to spatial resolution.

Since 1994, surface area of glaciers and glacierets analysed in this study has reduced as shown in Table 7. Toro 1 and Toro 2 have lost almost its entire surface. Esperanza seems to be stable as it was able to recover during the past decade and although it has lost 5% of its surface between 1994 and 2015. All the other glaciers show a continuous trend of surface area loss during the past 20 years.

Glacier	Glacier surface area sqkm			Loss between 1994 and last year
	1994	2004	Last year	
Los Amarillos	1,291	1,031	0,729	43,53%
Amarillo	0,378	0,317	0,143	62,12%
Estrecho	1,459	1,356	0,825	43,45%
Guanaco	2,077	1,942	1,374	33,84%
Toro 1	0,163	0,063	0,008	95,10% (until 2014)
Toro 2	0,199	0,060	0,007	96,48% (until 2014)
Esperanza	0,036	0,018	0,034	5,60%

Table 7. Surface aera loss over the last 2 decades

In order to characterise the temporal behaviour of the glacier surface area lost and to detect its correlations with rainfall and temperature, trends and correlation coefficients as shown in Table 8 were calculated.

	Trend (sqkm/a)	$r_{\text{Surface, Temperature}}$	$r_{\text{Surface, Precipitation}}$
Los Amarillos	-0,024	-0,4	0,2
Amarillo	-0,015	-0,4	0,4
Estrecho	-0,032	-0,4	0,8
Guanaco	-0,039	-0,5	0,5
Toro 1	-0,009	-0,2	0,5
Toro 2	-0,010	0,0	0,4
Esperanza	-0,001	0,4	0,1

Table 8. Trend in surface area lost and correlation coefficients

Precipitation at the mentioned climate stations Conay, Chollay and Vallenar are shown in Table 9. A couple of peaks can be observed which in general coincide with El Niño years.

Furthermore, compared to long-term observations as shown in Figures 6, 7 and 8, in 2004, 2006, 2012 and 2015, an absence of precipitation is observable. This also coincides with La Niña events that have been reported. During the past two decades, precipitation only in 1994 (Vallenar) and 2014 (Vallenar, Conay, Chollay) reached normal values.

Station	1994	1996	1998	2000	2002	2004	2006	2008	2010	2012	2014	2015
Vallenar	24,885	5,27	0,125	1,965	0,763	0,000	0,000	7,900	4.875	0,100	12.300	0,575
Conay	--	--	--	--	--	--	--	8,150	5,400	0,050	12,100	0,000
Chollay	--	--	--	--	--	--	--	8,15	5,525	0,175	11,65	0,525

Table 9. Average precipitation in mm during winter months

At all three stations, a positive temperature trend can be observed. Table 10 shows mean temperature during summer from 1994 onwards at Vallenar and from 2010 onwards for Conay and Chollay. In particular, summer of 2013 and 2015 shows huge variations in comparison to long-term climate observation (Figures 6, 7 and 8). Summer (December, January, February) mean temperature observed between 1982 and 2012 (Source: http://en.climate-data.org/) Vallenar station is 19.8°C; at Conay station 13.5°C; at Chollay station 14.4°C.

Our results indicate that all studied ice bodies have reduced in terms of extent over the past few decades and that there is a significant surface area loss in the glaciers and glacierets studied. Some of them show significant changes (Guanaco, Estrecho and Los Amarillos), whereas others seem to be more stable (Esperanza). Smaller ice bodies, glacierets, are more affected than glaciers. In particular, the Guanaco glacier shows major loss of surface area with a trend of –0.039 sqkm/a. It has already been reported by [55] that Guanaco, in comparison to other glaciers and glacierets in this area, shows major melt rates during summer months. On the other hand, the Esperanza glacier is the one which has almost remained stable. Its surface area loss has a tendency of –0.001 sqkm/a.

Station	1994	1996	1998	2000	2002	2004	2006	2008	2010	2011	2012	2013	2014	2015
Vallenar	19,7	19,9	21,0	19,4	19,3	17,2	--	--	18,3	19,0	21,5	22,7	22,3	23,3
Conay	--	--	--	--	--	--	--	--	19,6	18,5	20,7	22,6	20,1	24,4
Chollay	--	--	--	--	--	--	--	--	19,5	19,6	20.5	22,7	20,6	24,3

Table 10. Average temperatura in °C during summer months

In addition, considering climate variables like temperature and precipitation, surface area variation of glaciers and glacierets does weakly correlate with them. Only in case of Guanaco glacier, where the coefficient of correlation between surface temperature and surface-precipitation reaches values around 0.5, relationship between the variables can be interpreted as more dominant.

ENSO events can clearly be identified using MEI. Although in case of the Chilean Andes region, it is supposed that during El Niño years precipitation increases (as in 1998), this does not mean that glaciers and glacierets do not suffer surface area loss. But this does not mean that during La Niña years (e.g. 2010/11), surface area loss does accelerate neither.

A possible negative impact on the glaciers caused by the Pascua-Lama mining project or any other human activity was not considered, and our results do not indicate any correlation either. This coincides with a scientific report, which was recently published by [56]. They also could not find any evidence for surface area loss due to anthropogenic intervention in the study area. They attribute glacier variability to climate change and ENSO events. Nevertheless, due to contentious issues, this subject has to be analysed apart.

6. Conclusions

It has to be concluded that the overall climate situation at high latitudes of the Chilean Andes Mountain does have a negative impact on ice bodies. La Niña and El Niño events can be detected and it is possible to correlate them with variations in temperature and precipitation. As temperature during the past 25 years has augmented and precipitation has decreased, glaciers and glacierets have diminished their surface area.

There is evidence that lack of precipitation has a major impact on surface area loss. As an example, Esperanza glacieret was able to recover surface area loss in 2014 when precipitation average at all three stations was almost normal. This coincides with the results reported by [23]. Nevertheless, our results also indicate huge temperature variations and therefore we conclude that nowadays both climate variables have to be considered as responsible for glacier and glacieret surface area loss in the Commune of Alto del Carmen.

Although anthropogenic interventions in the study area are present, such as Pascua-Lama mining project, climate variability does play a major role in glacier changes. Nevertheless, this does not mean that human interference on ecosystems has to be tolerated. Every man-made alteration has to be reviewed critically and in particular in case of exploitation of natural resources, vital for flora and fauna, they have to be carried out complying with several standards protecting our planet. Nowadays, there are lots of technical possibilities, such as GIS and remote sensing that are well known and understood from geosciences, which allow a sustainable management of natural resources.

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