

Climate variations in a high altitude Alpine basin and their effects on a glacial environment (Italian Western Alps)

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RESUMEN

El principal objetivo de este estudio es evaluar la variación de los parámetros climáticos (temperatura, lluvia y nieve) medidos en dos estaciones meteorológicas (Formazza y Sabbione) que nunca antes se habían analizado, ubicadas en un ambiente glaciar (la cuenca del Sabbione en los Alpes occidentales italianos). El estudio se centra en la evolución climática de la cuenca alpina durante los últimos 60 años (1950-2012): el cambio climático ha causado una declinación glaciar pronunciada cuyo origen es el aumento de la ablación debido principalmente al incremento de la temperatura del aire y la reducción de la alimentación, a su vez ocasionada por la disminución de nieve fresca. La prueba de correlación cruzada muestra que la temperatura influye sobre la dinámica de la retracción glaciar más que la precipitación de la nieve. Se han identificado formas periglaciares y ligadas al permafrost (p. ej., suelos estructurados y glaciares de roca) en depósitos de glaciares provenientes de la Pequeña Edad de Hielo (PEH), lo cual evidencia la transición de un ambiente glaciar/proglaciar a un ambiente periglaciar aún en curso. Además, para identificar mejor el dominio periglaciar de la cuenca, se ha elaborado un mapa de la temperatura media anual del aire a partir de los análisis climáticos.

ABSTRACT

The main objective of this study is to evaluate the variations of climatic parameters (temperature, rain and snow) measured by two weather stations (Formazza and Sabbione) that have never been analyzed before, located in a high glacial catchment (the Sabbione basin in the Italian Western Alps). The study highlights the climatic evolution of the Alpine basin during the last 60 years (1950-2012): climate change has caused a pronounced glacial decline originated by ablation augmentation, due mainly to increasing air temperatures and to reduced alimentation caused by a fresh snow decrease. The cross-correlation test shows that temperatures affect the glacial retreat dynamics more than snowfall. Periglacial and permafrost landforms (e.g., patterned grounds, rock glaciers) have been identified within the Little Ice Age (LIA) glacial deposits, which indicate the ongoing transition from glacial/proglacial to periglacial environments. Furthermore, in order to better identify the periglacial domain in the basin, a map of mean annual air temperature (MAAT) was produced based on climatic analysis.

Keywords: Climate change, glacial decline, permafrost, Italian Western Alps.

1. Introduction

In the last years, several studies have demonstrated the existence of accelerated climate modifications that have affected the whole Earth, in particular the most vulnerable ecosystems such as mountainous regions. In the last 100 years (1906-2005), the global mean air temperature has increased 0.74 ± 0.18 °C, while in the Alps the increase in temperature is almost the double (Auer *et al.*, 2007; IPCC, 2007). Minimum air temperatures in the Alps have increased more than maximum air temperatures, which have shown a limited rise (Böhm *et al.*, 2001; Beniston, 2005; EEA, 2009). Moreover, there have been changes in precipitation amounts, especially in fresh snow, although they are not geographically homogeneous due to the heterogeneous morphology of the alpine region and the high complexity of alpine climate (Fратиanni *et al.*, 2009; Terzago *et al.*, 2010, 2012; Acquaotha and Frатиanni, 2013). In particular, in the Western Italian Alps a decrease in the fresh snow amount and snow cover permanence has been observed, which is closely related to the temperature rising as highlighted by the studies of Terzago *et al.* (2013), Acquaotha *et al.* (2014) and Frатиanni *et al.* (2015).

At high altitudes, climatic variations interact with glacial processes and influence the dynamics of alpine ecosystems. Mountain glaciers are the major fresh water source for people living in or nearby the adjacent lowlands of mountain ranges (Barnett *et al.*, 2005). The observed worldwide glacier retreat is thus an important concern for the availability of fresh water. For example, in 1850 the total area covered by Alpine glaciers was about 4500 km², while in 2000 it reduced to about 2270 km² (around -50%) (Cat Berro *et al.*, 2008). Italian alpine glaciers have also suffered a general retreat since the end of the Little Ice Age (LIA) and this regression has been accelerating in recent years due to the effects of climate warming. This trend has also been observed in the study area (Sabbione basin), where glaciers have been retreating since the second half of the 19th century.

The regression of glaciers allows the formation of periglacial environmental conditions in deglaciated areas with a range of cold/non-glacial processes (French, 2007). The periglacial environment is characterized by the presence of frost action and cryotic morphogenetic processes (Tricart, 1968; Péwé, 1969), and of permafrost, defined as “soil and/or

rock that has remained below 0 °C for more than two consecutive years” (Brown and Péwé, 1973).

In the present work, the data extracted from two high altitude meteorological stations (named “Formazza” and “Sabbione”) located in the Sabbione basin (Ossola Valley, North Piedmont, Italy) were analyzed for the first time in order to: (1) characterize the climate of the study area; (2) identify the trends of the main climatic parameters; (3) verify the existence of climatic conditions for the development of cryotic processes, using also the data recorded in other stations situated in the Ossola Valley (Agaro, Alpe Devero, Toggia and Vannino), and (4) investigate the morpho-climatic evolution of the basin, considering in particular the glacial/proglacial/periglacial transition. In this area several cryotic geomorphological occurrences have been highlighted during field surveys within deglaciated areas since the 1950s (Colombo *et al.*, 2013). Moreover, other meteorological stations (Canevarolo *et al.*, 2011) close to the study area, have been considered to estimate the basin areas included into the periglacial domain through mean annual air temperature (MAAT).

Indeed, according to the empirical definition proposed by French (2007), the MAAT < 3 °C is considered for the definition of periglacial domain. Guglielmin (2004) divides this domain, called “sensu lato” periglacial environment, in: (1) “sensu stricto” periglacial environment (MAAT between + 3 and 0 °C), and (2) permafrost environment (MAAT < 0 °C). Rainfall is less than 2000 mm/year (André, 2003; Boelhouwers, 2003).

Changes in glaciers are related to climatic variables through their energy and mass balance. Negative changes in the mass balance of a glacier result either from increased ablation or decreased accumulation, which are mainly determined by precipitation and air temperature (Leonelli *et al.*, 2011; Senese *et al.*, 2012). Thus, to understand the effects of climate evolution on glacial dynamics, two climatic parameters (summer air temperature and fresh snow) have been correlated with the frontal glacier regression of the northern Sabbione glacier for the time span 1978-2005.

2. Study area

The Sabbione basin is located in the Formazza Valley (Ossola Valley, Lepontine Alps, Italy, 46° 41' N, 8° 34' E), forming the upper basin of the Toce river and the Swiss border (Fig. 1). The major peaks of the

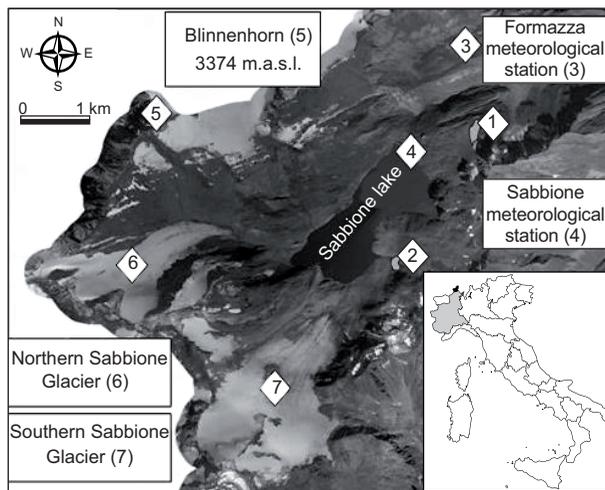


Fig. 1. Digital orthoimage of the study area: 1 and 2, rock glaciers; 3, Formazza meteorological station; 4, Sabbione meteorological station, 5, Blinnehorn peak; 6, Northern Sabbione Glacier; 7, Southern Sabbione Glacier (details in the text). Source: Ministero dell'Ambiente e della Tutela del Territorio e del Mare - Geoportale nazionale, 2006 (wms service available at: http://wms.pcn.minambiente.it/ogc?map=/ms_ogc/WMS_v1.3/raster/ortofoto_colore_06.map).

basin are: Blinnehorn (3374 masl; Fig. 1[5]), Corno di Ban (3027 masl), Gemelli di Ban (2946 masl), Punta d'Arbola (3235 masl) and Hohsandhorn (3182 masl).

A storage lake of 1.23 km² (about 26 million m³) is located in the basin, which gathers the ablation waters of the glaciers situated within the area; the main glaciers are the northern Sabbione glacier (Fig. 1 [6]) and the southern Sabbione glacier (Fig. 1 [7]) (about 3.8 km² of total covered area in 2007), the Blinnehorn glacier and the Gemelli di Ban glacier. The major glaciers lie in the northwestern sector of the basin, between Punta d'Arbola and Blinnehorn. Glaciological campaigns, literature data review and field surveys have allowed to quantify the regression of the northern and southern Sabbione glaciers. These glacial fronts have retreated approximately 2 km in the period 1885-2011, with the second one showing a more pronounced reduction due to the effect of calving at the glacier front, after the creation of the artificial lake in the 1950s (Mazza and Mercalli, 1992; Mazza, 1993; Mazza, 2007).

A large amount of glacial deposits (3.2 km²) outcropped after the glaciers retirement. Periglacial landforms have been identified in these deposits

(Colombo *et al.*, 2013), deriving from freeze-thaw cycles (e.g., patterned ground and gelifluction lobes) and permafrost processes (rock glaciers and protalus rampart) (Barsch, 1996; Baroni *et al.*, 2004). In particular, two active rock glaciers are recognized within the basin: the biggest is a talus rock glacier situated within a deglaciated area, probably since the end of the last glacial maximum (LGM) (Fig. 1 [1]); here a bottom temperature of the snow cover (BTS) (Haeberli, 1973; Guglielmin and Tellini, 1994) measurement campaign was performed by the Agenzia Regionale per la Protezione Ambientale (Regional Agency for Environmental Protection, ARPA) of Piedmont in the late 2011 winter, showing the likely presence of permafrost. The other one (Fig. 1 [2]) is a debris rock glacier located in the lateral moraine of the southern Sabbione glacier, retreated since the 1950s as shown in aerial photos.

So, the Sabbione basin is an interesting area of study since it is characterized by various typologies of environment in evolution (glacial and periglacial), influenced also by an artificial lake that has conditioned in particular the glacial reduction.

3. Data and methods

The data sets recorded in the meteorological stations Formazza and Sabbione cover the periods 1988-2012 and 1950-2012, respectively. Formazza is an automatic weather station located in the Pian dei Camosci area (2453 masl) and it belongs to the weather regional network managed by ARPA Piemonte. Sabbione is a manned weather station situated in the dam area (2470 masl) owned by the Enel power company, which manages also the hydroelectric plant; it is the nearest station to the glaciers (about 2.4 km in 2010), which allows having direct measurements of meteorological variables with long continuity.

The elimination of months with daily data lower than 80% (Sneyers, 1990) and a quality control (QC) with the RCLimDex software (Zhang and Yang, 2007) were performed before the analysis (Acquaotta and Fratianni, 2014; Acquaotta *et al.*, 2015). The QC allowed to identify all missing values, unreasonable values (such as daily precipitation amounts lower than zero and maximum temperatures lower than minimum temperatures) and outliers in daily values. At the same time, a historical research on the meteorological stations was carried out; breaks (called metadata) in the series homogeneity, either

due to changes of location or of instrument, were determined. We consulted the hydrological annals (archives of the Hydrographic and Mareographic National Service), which report yearly the geographic coordinates (latitude, longitude and elevation) and the instrument type for each station. Furthermore, we inspected the original records on which potential breaks and changes of location or instrumentation have been marked. Then, to evaluate the degree of homogenization of the series we compared our data with the neighboring stations (Agaro, Alpe Devero, Toggia and Vannino) (Peterson *et al.*, 1998; Wijngaard *et al.*, 2003; Acquotta *et al.*, 2009; Venema *et al.*, 2012).

For the Sabbione station metadata was not present. The station was not moved, nor the neighboring environment was modified. The comparison with the neighboring stations did not highlight discontinuities in the series, so the data can be considered homogeneous. Formazza station data was not homogenized either, because the series has not metadata and the comparison with other neighboring meteorological stations has shown good results.

The values from both stations were aggregated on monthly, seasonal and annual basis obtaining an annual average for the main climatic parameters (temperature, precipitation, snow and wind [the last one only for the Formazza station, which is equipped with anemometer]).

Trends were calculated only for the longest time dataset of the Sabbione station; the parameters analyzed were maximum and minimum air temperatures, maximum and minimum summer air temperatures, cumulated precipitation, number of rainy days, cumulated fresh snow, snow depth, number of snowy days, period of snow cover absence and number of freeze-thaw daily cycles (days with maximum air tempera-

ture $> 0\text{ }^{\circ}\text{C}$ and minimum air temperature $\leq 0\text{ }^{\circ}\text{C}$). To evaluate variations in extreme events the climatic indices and related trends were also calculated. These indices (Table I) were selected from the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI), which has been coordinating an international effort to develop, calculate and analyze a suite of climate extremes indices (Klein Tank *et al.*, 2009). The non-parametric test of Mann-Kendall was used to verify the statistical significance, assuming a 95% probability level (Sneyers, 1990, 1992).

The standardized anomaly index (SAI) (Hereford *et al.*, 2002; Nigrelli and Collimedaglia, 2012) was also calculated for fresh snow, snow depth, and annual and summer (June-September) temperatures at the Sabbione station for the reference period (1971-2000), in order to identify climatic anomalies. The SAI is calculated as a difference between a datum and the sample mean divided by the standard deviation:

$$SAI = (x - \mu) / \sigma$$

where x is the datum, μ is the mean and σ is the standard deviation. Furthermore, the 5-yr moving average was calculated.

As a first-order approximation, the long-term MAAT can be used to delineate mountain regions and altitudinal belts with permafrost occurrences (Haeberli *et al.*, 2010). In the present work, statistical analyses combined with a literature review of climate data series allowed to evaluate the relationships between climatic parameters and altitude within the basin. A MAAT map was realized for the reference period (1971-2000) in order to estimate the distribution of areas with potential presence of cryotic processes and permafrost, by using air temperature data recorded at Sabbione (2470 masl) and other stations situated in the Ossola Valley, such as Agaro (1600 masl), Alpe Devero (1634 masl), Toggia (2165 masl) and Vannino (2177 masl) (Canevarolo *et al.*, 2011). The vertical temperature lapse rate was calculated using the data extracted from the five weather stations, and the statistical significance of correlation obtained from ordinary linear least square regression analysis was verified by using the non-parametric test of Mann-Kendall.

Finally, in order to understand how climatic conditions affect the glacial retreat dynamics, the annual

Table I. Climatic indices used in this work.

CDD	Consecutive dry days, maximum number of consecutive dry days ($R_{day} < 1\text{ mm}$).
CWD	Consecutive wet days, maximum number of consecutive wet days ($R_{day} \geq 1\text{ mm}$).
FD0	Frost days, number of days with frost (daily $T_{min} < 0\text{ }^{\circ}\text{C}$).
ID0	Ice days, number of days with ice (daily $T_{max} < 0\text{ }^{\circ}\text{C}$).

and cumulated frontal regression of northern Sabbione glacier was analyzed. The data were acquired for the time-lapse 1978-2005 (which is the most complete acquisition period for the investigated glacier) using the campaign results of the Comitato Glaciologico Italiano (Italian Glaciological Committee, CGI). Then, the cross-correlation test was applied (Chen, 1982; Childers, 1982; Kearey and Brooks, 1991; Telford *et al.*, 1992; Belloni *et al.*, 2001). Summer temperatures (June-September) that influence the snow permanence on the glaciers, as well as the glaciers mass balance, annual fresh snow (from September to August of the following year, to compare with the glacier's data collected every September), and glacier cumulated regression, were used as input data.

4. Results and discussion

The annual average values of the main climatic parameters are shown below.

With the preliminary control of the Formazza series for the time-frame November 1988-June 2012, 19 of 284 months (6.7%) with daily data lower than 80%, corresponding to a maximum of six non-consecutive days in a month, were deleted. The analysis of air temperature shows an annual air temperature of -0.2 °C; the coldest month is January (-6.9 °C) and the warmest is August (7.5 °C). The most extreme recorded values are: -28.3 °C (February 7, 1991) for the minimum air temperature and 19.4 °C (September 8, 1998) for the maximum air temperature. The number of freeze-thaw cycles is 123 and these are mainly concentrated in spring and autumn.

The rainfall is 995.1 mm, with a maximum of 1311.8 mm in 1999. The precipitation is concentrated in warmer months, especially June and September. The number of rainy days is 112, with a maximum of 138 days in 2006. The pluviometric regime cor-

responds to the continental type with a principal maximum in summer, secondary maximum in autumn, principal minimum in winter, and secondary minimum in spring.

The fresh snow is 696.2 cm. Snowfall is more abundant in November, with an average of 143 cm. The number of snowy days is 60 and the maximum number of snowy days occurs in November (10). The snow depth is 97.1 cm and the extreme value was recorded on April 29, 2009 when 457 cm of snow were measured. The nivometric regime is unimodal with a spring maximum.

The wind speed is 2.5 m s⁻¹ with an absolute maximum gust of 36.1 m s⁻¹ registered on March 29, 1995. The anemometric regime is bimodal with two prevailing directions: North-East, typical of spring and summer, and South-West, predominant during autumn and winter.

The data acquisition time-frame (December 1950-June 2012) of the Sabbione station shows that temperature is -0.9 °C. The coldest month is January (-8.0 °C) and the warmest is August (7.2 °C). The measured extreme values are: -32 °C (January 6, 1985) for the minimum air temperature and 21 °C (August 13, 2003) for the maximum air temperature. The number of freeze-thaw cycles is 116 and they occur mainly during spring and autumn.

The precipitation is 1034.8 mm, with a maximum of 1601 mm recorded in 1977. The rainfall is concentrated in warmer months, especially June and August. The annual average number of rainy days is 127, with a maximum of 144 days recorded in 1972. The pluviometric regime is continental.

The fresh snow is 741.3 cm. Snowfall is more abundant in November, with an average value of 123 cm. The number of snowy days is 64 and the maximum number of snowy days occurs in November (10). The snow depth is 128.3 cm, with a

Table II. Sabbione station trends (1951-2011).

Climatic parameters	Trend	Statistical significance (p -value < 0.05)
Maximum temperature	0.03 ± 0.01 °C/year	Significantly
Minimum temperature	0.04 ± 0.01 °C/year	Significantly
Rainfall	1.15 ± 1.9 mm/year	Non significantly
Rainy days	-0.25 ± 0.11 days/year	Non significantly
Fresh snow (HN)	-3.17 ± 1.35 cm/year	Significantly
Snow depth (HS)	-0.82 ± 0.27 cm/year	Significantly
Snowy days	-0.06 ± 0.09 days/year	Non significantly
Snow cover absence	0.08 ± 0.1 days/year	Non significantly

maximum value of 700 cm observed on February 15, 1951. The nivometric regime is unimodal with a spring maximum. The snow cover absence is of 102 days, concentrated in the months of July, August, September and October.

The trends of the Sabbione station (1951-2011) are shown in Table II.

After an increase in the 1950s-1960s and a decrease during the 1970s-1980s, maximum and minimum temperatures have risen constantly. The snow (HN and HS) shows an opposite trend: it decreased in the 1950s-1960s, increased during the 1970s-1980s and decreased again in the following years (Fig. 2a, b).

For the climatic index, consecutive dry days and consecutive wet days have a non-significant positive trend. Frost days show a statistically significant

decrease of -0.68 ± 0.13 days/year (Fig. 2c) and ice days present a statistically significant decrease of 0.49 ± 0.17 days/year (Fig. 2d). These results indicate a general rise in temperature that limits the frost and ice periods.

The fresh snow and snow depth SAIs are generally included between +1 and -1. From 1975 to 1986, the SAI was between +1 and +2, indicating a positive moderate anomaly; during the last 15 years the SAI has been often included between -1 and -2, indicating a negative moderate anomaly (Fig. 3).

The annual temperatures SAI shows negative values at the start of the 1950s, in the 1960s and in the 1980s. The positive values are concentrated at the beginning of the 1970s and from the late 1980s to the end of the time span analyzed, evidencing a recent warming (Fig. 4a).

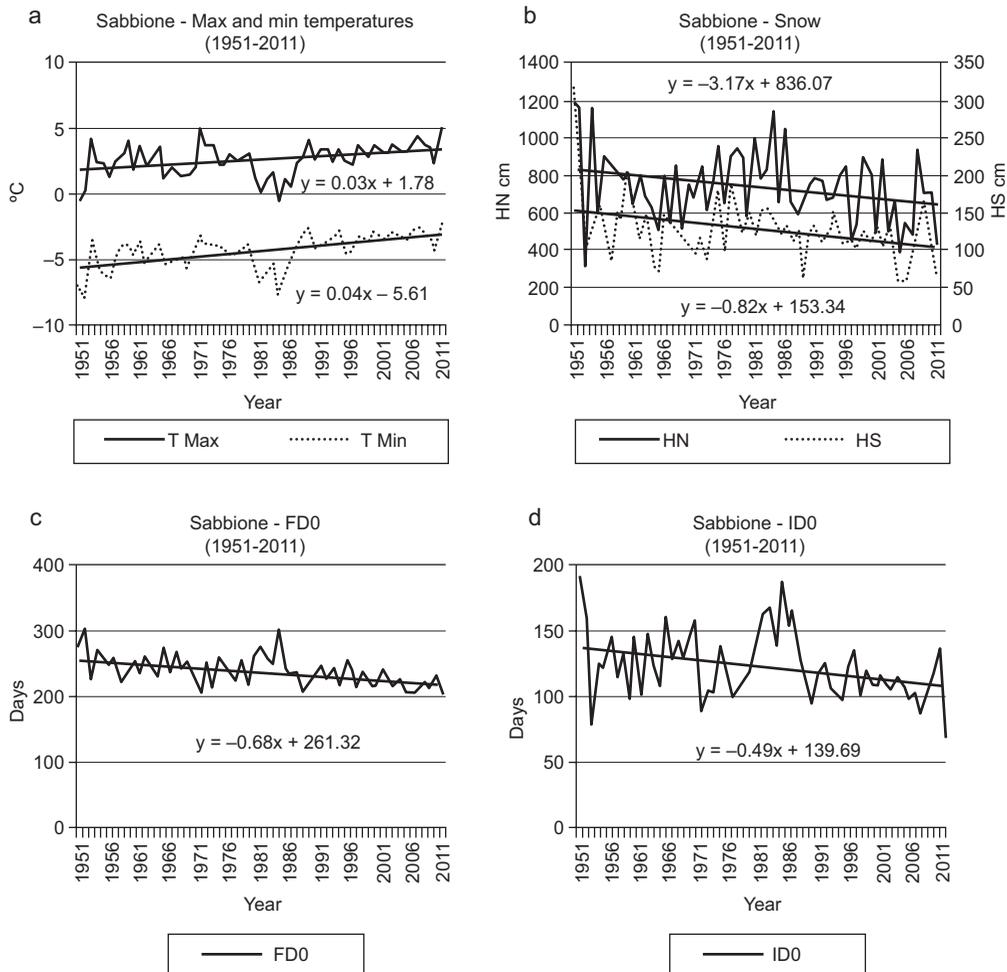


Fig. 2. Results of the Sabbione station analysis: (a) Temperature trends; (b) Snow trends; (c) Frost days trend; (d) Ice days trend. HN: fresh snow; HS: snow depth.

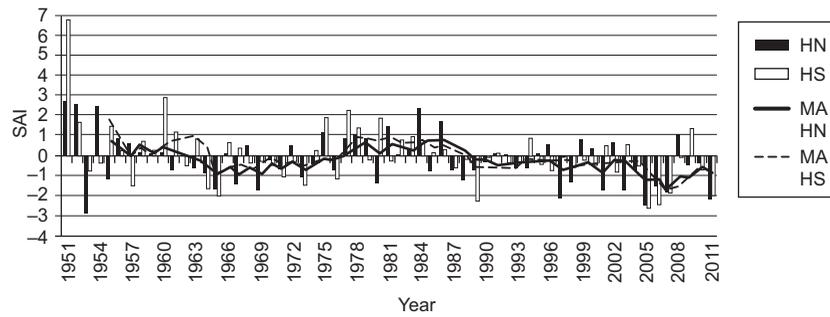


Fig. 3. SAI of annual snow depth (HS) and fresh snow (HN) series for Sabbione (1951-2011) with a 5-yr moving average (MA). The continuous line indicates MA for HN, and the dotted line indicates MA for HS.

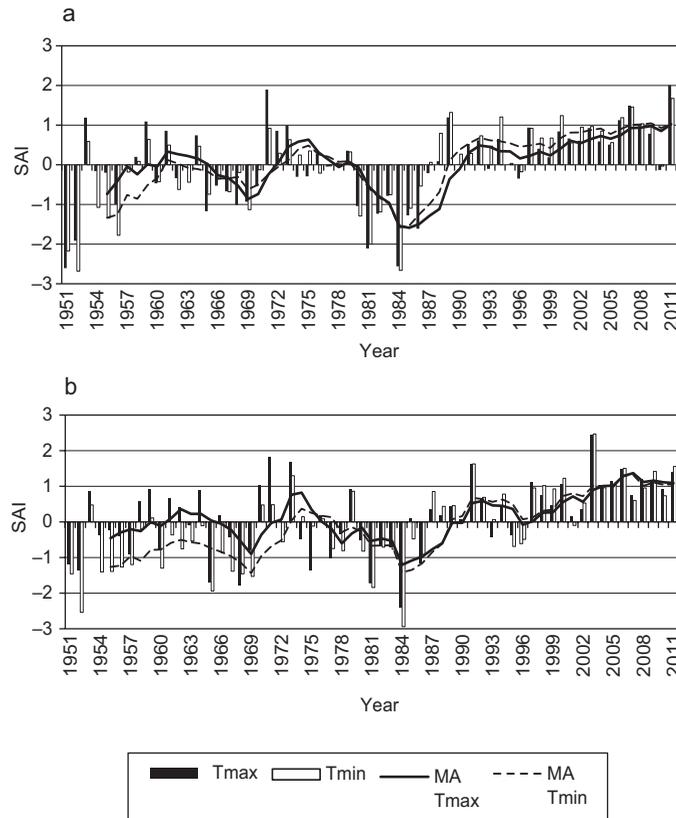


Fig. 4. SAI of annual (a) and summer (b) temperatures series for Sabbione (1951-2011) with a 5-yr moving average (MA). The continuous line indicates MA for Tmax, and the dotted line denotes MA for Tmin.

The summer temperatures SAI follow the previous indices but they are more marked. In particular, 1984 is the coldest year with a SAI of -2.5 , and 2003 is the warmest year with a SAI of $+2.3$ (Fig. 4b).

The average annual values of the main climatic parameters were associated with those extracted from other Ossola weather stations, analyzed in previous

studies: Agaro, Alpe Devero, Toggia, and Vannino (Canevarolo *et al.*, 2011), situated within 15 km of the Sabbione station (Table III). The elevation gradient for air temperature, precipitation, fresh snow and snow depth was calculated for the time-frame 1971-2000 applying the statistical test of Mann-Kendall to verify the statistical significance.

Table III. Average annual values of the main climatic parameters for Ossola Valley in the 30-yr period from 1971 to 2000.

Station	Agaro	Alpe Devero	Toggia	Vannino	Sabbione
Altitude (m)	1600	1634	2165	2177	2470
T	5.4	3.1	0.5	0.4	-0.9
P	1317	1617	1244	1238	1041
Rd	116	123	135	128	124
HS	30	48	86	82	128
HN	380	537	714	643	768
Sd	34	38	62	49	62

T: temperature (°C); P: precipitation (mm); Rd: rainy days; HS: snow depth (cm); HN: fresh snow (cm); Sd: snowy days.

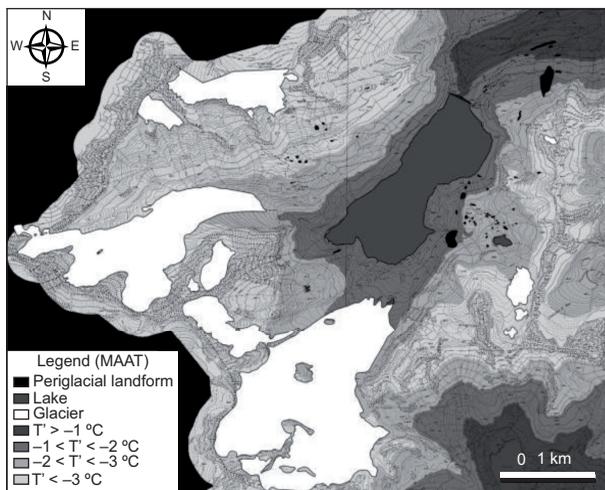


Fig. 5. Mean annual air temperature map.

The average value of the thermal adiabatic gradient is $0.64\text{ }^{\circ}\text{C}/100\text{ m}$; precipitation shows a significant decrease of $-41 \pm 11\text{ mm}/100\text{ m}$; the snow depth has a significant increase of $9 \pm 1\text{ cm}/100\text{ m}$; the fresh snow shows a non-significant increase of $34 \pm 7\text{ cm}/100\text{ m}$.

From these data, a mean annual air temperature map was produced, based on a 5 m digital terrain model (DTM) of the Piedmont region (Fig. 5). Three temperature thresholds were characterized:

$-1\text{ }^{\circ}\text{C}$, indicating the lower altitudinal limit of discontinuous permafrost and potential presence of some permafrost indicator landforms (Haeberli, 1985; Haeberli *et al.*, 2010);

$-2\text{ }^{\circ}\text{C}$, indicating environments in which frost action dominates (French, 2007);

$-3\text{ }^{\circ}\text{C}$, lower limit of areas affected by the likely presence of large quantities of permafrost (Haeberli *et al.*, 2010).

The MAAT map shows that glaciers are mainly located within the $\text{MAAT} < 3\text{ }^{\circ}\text{C}$ class (with the exception of the middle and frontal zones of northern and southern Sabbione glaciers), suggesting a probable presence of suitable conditions for permafrost aggradation within debris deposits and outcropping bedrock surrounding the glaciers. The two rock glaciers in the basin, which are considered as permafrost indicators, are included in the $-2\text{ }^{\circ}\text{C} < \text{MAAT} < -1\text{ }^{\circ}\text{C}$ condition and their fronts are located at 2475 and 2505 masl.

Periglacial landforms resulting from frost heaving and frost sorting processes, such as non-sorted circles and frost-boils, were found within debris deposits, in particular till. The 90% of these periglacial landforms in the basin is located at altitudes higher than 2500 masl and in areas with MAAT between -1 and $-2\text{ }^{\circ}\text{C}$, where debris deposits are predominant.

The frost action becomes dominant above 2650 masl, where MAAT is below $-2\text{ }^{\circ}\text{C}$, while the lower limit of zones characterized by the likely presence of large quantities of permafrost ($\text{MAAT} < -3\text{ }^{\circ}\text{C}$) is located above the threshold altitude of 2820 masl.

Finally, to analyze the correlation between climatic parameters and glacial regression, we have considered the cumulative glacier's regression, which permits to avoid incorrect annual data comparison (Guggino Picone and Gramignani, 1966) due to limited missing values in annual glaciological campaigns (e.g., lack of measurements during the period 1984-1985). We have also compared the annual frontal regression with climatic parameters (temperatures and fresh snow), but the correlation is low; the values are both positive and negative and they show a random distribution.

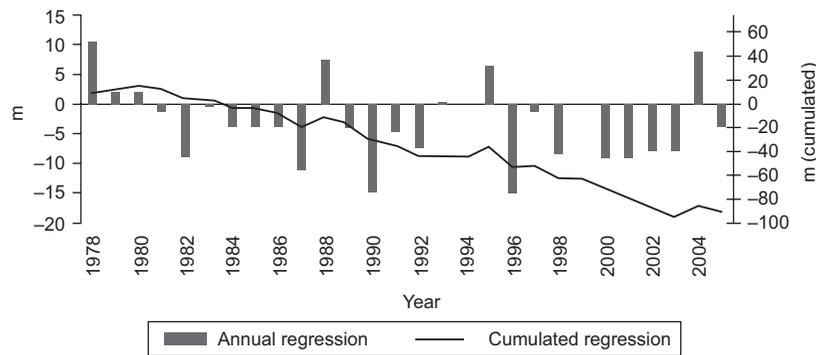


Fig. 6. Northern Sabbione glacier regression.

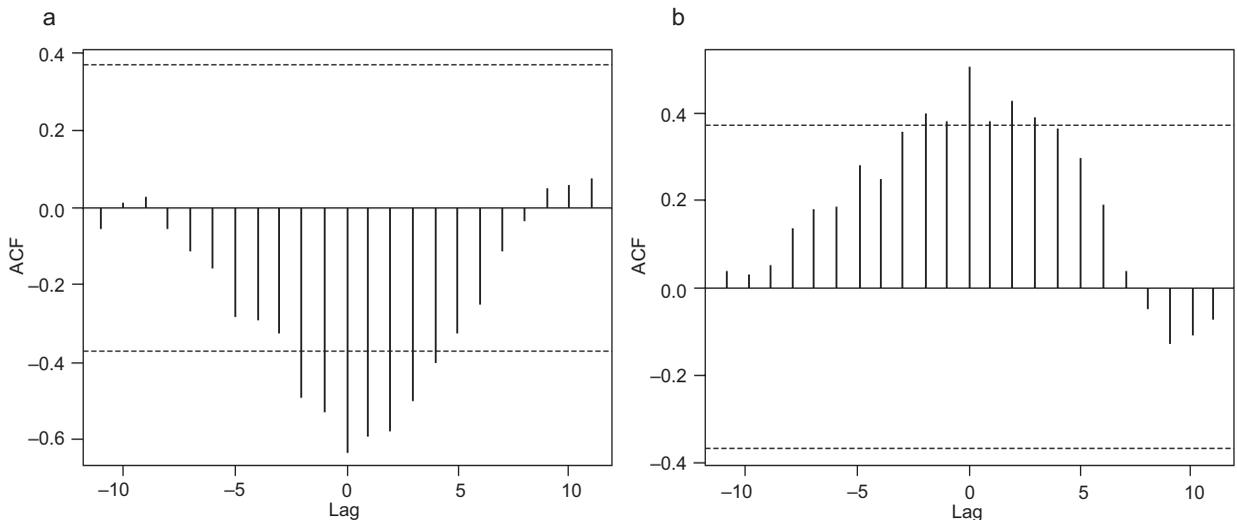


Fig. 7. (a) Correlation between maximum temperatures and glacier cumulated variations. (b) Correlation between fresh snow and glacier cumulated variations. The dotted lines highlight the 95% significant level. Y-axis represents the cross-correlation values and X-axis the lags, 1 lag = 1 year.

The analysis of frontal regression of the northern Sabbione glacier between 1978 and 2005 shows that the glacier underwent a cumulative reduction of -90 m (Fig. 6). The correlation between glacier variations (retreat) and maximum temperature is negative. The maximum correlation (-0.628) is for lag = 0 highlighting an immediate response of the glacier with the maximum temperature values (Fig. 7a). Significant values of correlation were estimated also from lag = 1 to lag = 4 indicating that high values of Tmax likely lead to the reduction of the glacier during the four following years.

The glacier dynamics appears less influenced by the fresh snow parameter. The correlation is higher than 0.4 (which is a good correlation threshold) only at lag = 0 (0.506) (Fig. 7b) showing an immediate response of the glacier with the fresh snow influence.

5. Conclusions

The Sabbione basin is characterized by the presence of periglacial domain with a mean annual air temperature comprised between -1 and 3 °C (French, 1996, 2007); in particular, the basin is located in a permafrost environment, according to the definitions proposed by Guglielmin (2004), with MAAT below 0 °C and rainfall below 2000 mm/year (André, 2003; Boelhouwers, 2003).

The data derived from the analysis of the long period Sabbione station (located near the glacier) monitoring over time, confirm the ongoing climatic conditions in the Alps. The climatic evolution of the studied area since the end of the LIA has caused a substantial decrease in glacial masses. In particular, the climatic trends of the past 60 years are the main cause of the pronounced glacial decline which is

originated primarily by ablation augmentation, due to the thermic increase in air temperatures, and secondly by alimentionation reduction caused by decrease in snow fresh.

This study, as other studies conducted on several sites of the Ossola Valley, evidences the ongoing climate evolution in the Western Alps. In particular, glaciers show a highly susceptible respond to the effects of summer temperatures and fresh snow, as demonstrated by the present work results about SAI and cross-correlation analyses. Furthermore, the regression of glaciers allows the instauration of cryotic processes in deglaciated areas, with the formation of periglacial landforms.

If the current climatic trends continue in the future, a further and accelerated glacial reduction is expected as function of temperature and solid precipitation influence. Long-term in situ measurements are needed to assess the complex interactions between climate and glaciers in order to better understand the effective ongoing processes and to provide data for reliable projections of future glacier evolution.

At high altitude, the Alps are characterized by the presence of glacial and periglacial environments which are currently susceptible to significant transformations, as shown in this case study; thus, the analysis of the relationships among climate, glacial and periglacial environments is important to understand the future evolution of high alpine landscape under climate change effects.

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