

Climate variability and Alpine glaciers evolution in Northwestern Italy from the Little Ice Age to the 2010s

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Received: 23 July 2014 / Accepted: 3 November 2014 / Published online: 25 November 2014
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Abstract In this work, we analyze climate variability and glacier evolution for a study area in the Northwestern Italian Alps from the Little Ice Age (LIA) to the 2010s. In this area, glacier retreat has been almost continuous since the end of the LIA, and many glaciers are now extinct. We compared glaciological and climatic data in order to evaluate the sensitivity of glaciers to temperature and precipitation trends. We found that temperatures show significant warming trends, while precipitation shows no clear signal. After the 1980s, the total number of positive trends in temperature increased, particularly minimum temperature. The latter does not seem to be the only cause of glacier shrinkage but rather on acceleration of an ongoing trend documented since the end of the LIA. In some rare cases, the effects of warming trends on glacier dynamics have been accentuated by a concomitant decrease in precipitation. We hope that this study will contribute to increase the knowledge of the relationships between climate variation and glacier evolution in the Greater Alpine Region.

1 Introduction

Glacier evolution is directly driven by climatic factors. For this reason, and due to the clear visibility of glacier growth and shrinkage to the public, glaciers have been recognized as the

best terrestrial indicators of climate change (IPCC 2013). The most direct climatic signal is provided by surface mass balance while glacier fluctuations provide delayed and modulated signals (Haeberli and Hoelzle 1995). Nevertheless, these latter are the oldest and most frequent measurements available worldwide and are thus often used for climate reconstruction (Oerlemans 2005).

In the European Alps, general glacier retreat started at the end of the Little Ice Age (LIA, 1850 approximately), briefly interrupted by temporary advances occurring during the 1920s and the 1970s. Since the 1980s, glacier shrinkage has been continuous with a marked acceleration between the end of the 1980s and the beginning of the 1990s (Paul et al. 2004; Citterio et al. 2007; Diolaiuti et al. 2011; UNEP 2014). It has been estimated that the overall loss of glaciated surface in the European Alps has been as much as 50 % between 1850 and 2000 (Zemp et al. 2008), but ice volume loss has been much higher, given that glaciers have lost approximately two thirds of their volume since 1850 (EEA 2012).

Climate change in the Alps has been extensively studied by the project “HISTALP-Historical Instrumental climatological Surface Time series of the Greater Alpine Region (GAR)”. This area has been defined as a region lying between 4 and 19° E and 43–49° N (HISTALP 2014). The HISTALP database contains monthly homogenized time series data sets covering the last 250 years, dating back to 1760 for temperature and to 1800 for precipitation. Between the late nineteenth and the early twentieth century, the mean temperature in the GAR has been observed to increase by around 2 °C, i.e., more than twice the rate of average warming of the Northern Hemisphere, with a gradual increase in precipitation in the Northern Alpine region and a decrease in the Southern Alpine region. Within the GAR, the climatic element with the highest spatial variability is precipitation, with 10 % less total annual precipitation observed in the SW region (includes our study area) over the last 30 years.

Electronic supplementary material The online version of this article (doi:10.1007/s00704-014-1313-x) contains supplementary material, which is available to authorized users.

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Glacier behavior is largely homogenous on a global scale (IPCC 2013); however, response time of specific glacierized sectors or individual glaciers to global climate change is not immediate, and the magnitude of glacier retreat is not linearly correlated with the magnitude of climate change. It depends on topography and glacial morphology and on locally specific climatic conditions and trends (Oerlemans 2001). Therefore, in order to use glacial fluctuations for the reconstruction of past climate, or for modeling the future evolution of the glacial resource, topoclimatic conditions, orography, and glacial morphology cannot be ignored (Barry 2008; Winkler et al. 2010).

This work aims to contribute to the knowledge of spatial diversity of glacier changes in response to climate variations, with a comparative analysis of local climate time series and multitemporal glaciological data, carried out for five glacierized areas at the Southwestern end of the GAR. Glaciers in the study area are quite small and therefore usually respond promptly to climate forcing. For this reason, they are particularly suitable for the analysis of climate-dependent variations that are the object of our work. We used time series of land-based weather stations, rather than gridded dataset (Bonanno et al. 2014), and aggregate values of glaciological parameters as they are, for the different mountain sectors, more representative than single glaciers (Winkler et al. 2010). The work is articulated in three main parts: we first analyzed changes of the main glaciological parameters since the end of the LIA, in the Southwestern Italian Alps; we then carried out a trend analysis on temperature and precipitation time-series of the selected weather stations of the study area covering the period 1950–2012, and of two long-time series of the HISTALP Project; finally, we compared glaciological and climatic data in order to assess the sensitivity of glaciers to fluctuations in temperature and precipitation.

The present contribution integrates recent studies carried out in other parts of the Italian Alps, some with different methodological approaches (Calmanti et al. 2007; Diolaiuti et al. 2012a, b; Cerutti 2013; D'Agata et al. 2014).

2 Study area

The study area is located in Northwestern Italy, which is part of the Southwestern GAR (6.4–7.2° E, 44.1–45.2° N).

It includes five Alpine sectors that are from North to South: (i) the Orco and Soana Valleys (OSV), highest altitude Gran Paradiso, 4061 m; (ii) the Lanzo Valleys (LV), highest altitude Uia di Ciamarella, 3676 m; (iii) the Susa Valley (SV), highest altitude Pierre Menue, 3506 m; (iv) the Po and Varaita Valleys (PVV), highest altitude Monviso, 3840 m; (v) the Stura di Demonte and Gesso Valleys (SGV), highest altitude Cima Sud dell'Argentera, 3297 m (Fig. 1).

The Southwestern Italian Alps are composed of different lithotypes that have an important influence on chain

orography and morphology affecting the distribution and size of glaciers. High elevations of the Western Alps along with suitable climatic conditions favored, from 1.2 million years B.P. onward, the formation and development of many valley glaciers that deeply molded the topographical setting of the area (Carraro and Giardino 2004; Ehlers 2007).

Glacier advances and retreats during the Quaternary are locally recorded by lateral and frontal moraine systems. In most of the study area, in addition to the Pleistocenic moraines, late Holocene glacial landforms are preserved and related to the overall phase of glacier advances and shrinkage during the LIA, around between 1350 and 1850 A.D., as a consequence of climate changes (Kuhn 1981; Oerlemans 2001). Areas vacated by glaciers were then intensely reshaped by fluvial and gravitational processes creating the landscapes we see today.

Nowadays, glacial bodies preserved in the study area are extremely reduced in number and extent compared to the past but also to glaciers in other parts of the alpine chain. This is partly due to the orientation of the head basins, which all drain eastward toward the Po Plain. In the five Alpine sectors, the mean glacier orientation is as follows: from NW to S in the OSV, from N to S in LV, from N to SE in the SV and PVV, from NW to E in the SGV—thus facing E, SE, and S, orientations unfavorable to ice preservation (Gardent et al. 2014).

Governed by the interaction between mountain range systems and the general atmospheric circulation, the Alpine climate is highly complex, with very different climate regimes typical of Mediterranean, continental, Atlantic, and polar areas (Barry 2008). Climate in Western Italian Alps is characterized by cold, dry winters and warm, wet summers. The mean monthly temperatures have a unimodal trend: the hottest month is July and the coldest is January. The mean monthly precipitation has a bimodal trend with two maxima, the principal one in spring and the secondary one in autumn, and two minima, with the principal one in winter and the secondary one in summer. Climatic conditions show significant differences in the quantitative values of precipitation and temperature regimes in the five investigated Alpine sectors. For the 1961–2007 time period, from North to South, the total annual precipitation shows values of about 1200 mm in the OSV and LV, 800 mm in the SV, 900 mm in the PVV, and about 1000 mm in the SGV (Società Meteorologica Subalpina 2008). In these five Alpine sectors, during 1971–2000, the annual minimum and annual maximum air temperatures show an increase of about 2–3 °C in the mean values proceeding from North to South (ARPA Piemonte 2014b). This increase is due to the presence of different climate regimes: more continental in the North and more Mediterranean in the South. These differences in the climatic conditions have suggested that the study area be divided into these five Alpine sectors.

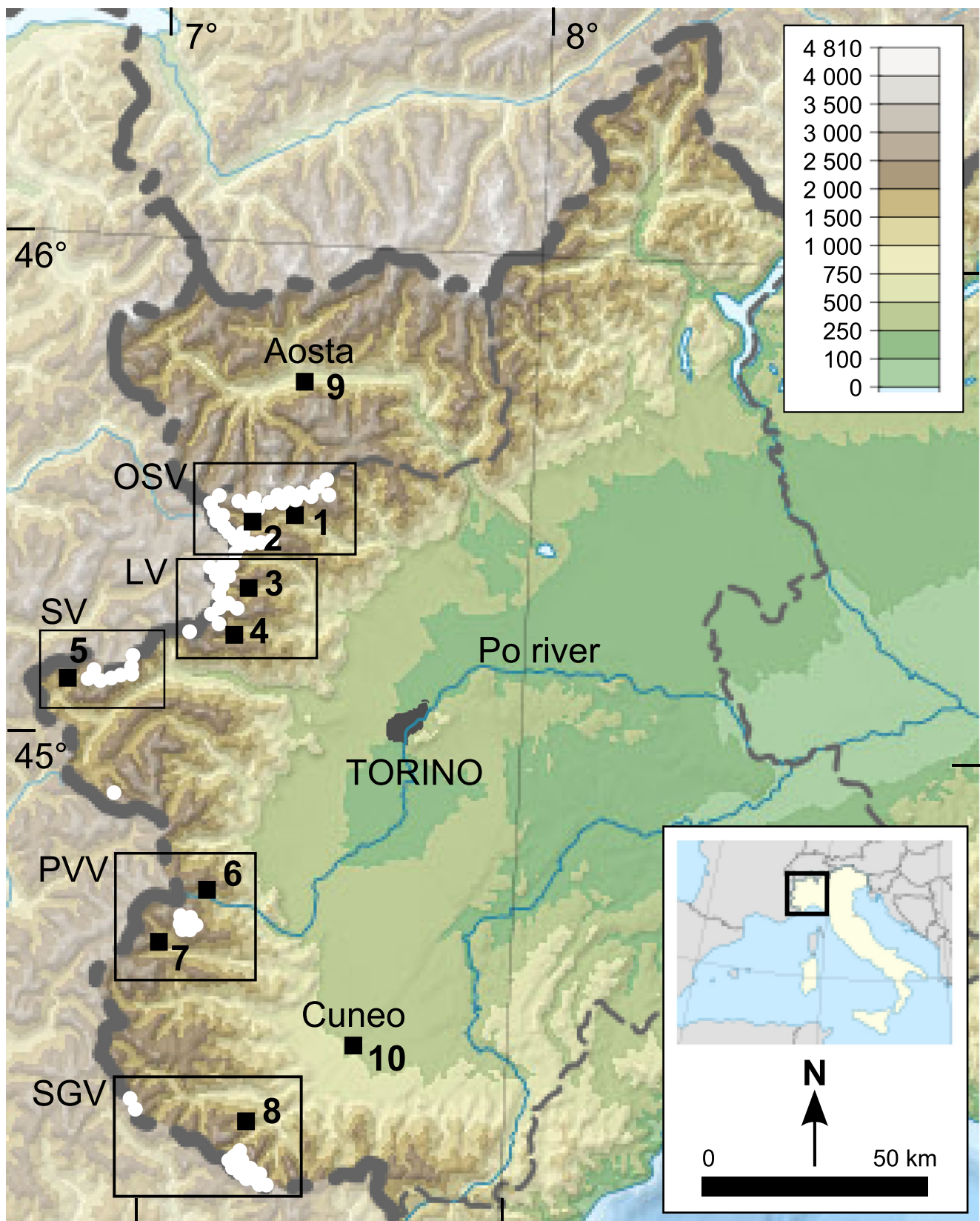


Fig. 1 Schematic map of Northwestern Italy, with the five Italian Alpine sectors (*OSV* Orco and Soana Valleys, *LV* Lanzo Valley, *SV* Susa Valley, *PVV* Po and Varaita Valleys, *SGV* Stura di Demonte and Gesso Valleys).

The map shows the LIA glaciers (*white circles*), and the location of each weather station (*black square and number*, see Table 2). The location of the two HISTALP stations, Aosta (9) and Cuneo (10) is also shown

3 Data and methods

In this section, we first illustrate the data and the methods we used for the glaciological investigations, then those we used for the analysis of climate variations.

3.1 Glaciological data

Information relating to the glaciers of the study area is contained in the following sources: (i) official topographic maps of the Italian Military Geographical Institute (Istituto Geografico Militare Italiano, IGM), at scale 1:25,000, drawn from surveys carried out at the beginning of the XX century (1925–1934); (ii) national glacier inventory (CNR-CGI, Consiglio Nazionale delle Ricerche—Comitato Glaciologico Italiano 1961), consisting of a form for each inventoried glacier, including glacier outline drawn on the 1:25,000 IGM topographic map, a terrestrial photo, and values of the main glaciological parameters (www.glaciologia.it); (iii) national glacier inventory realized in the framework of the initiative “World Glacier Inventory” (WGI, promoted by the National Snow and Ice Data Center of Boulder, Colorado, and published in 1989, http://nsidc.org/data/glacier_inventory), known as “Catasto Secchieri”, dated to 1983 for the study area. It consists of a form for each glacier including the glacier outline drawn on the 1:25,000 IGM topographic map: glaciological data contained in this inventory were derived by aerial photo analysis and measured by hand on the map; (iv) database realized in the framework of the project “GlaRiskAlp” (Glacial Risks in the Western Alps, project No. 56, 2007–2013 ALCoTra program) containing glacier outlines and morphological features at the end of the LIA and in the 2000s. Glaciological data produced in the framework of the project “GlaRiskAlp” were derived from orthophoto analysis supported by a geographic information system (GIS). Glacier areas were calculated through the specific GIS function, while the elevation values were derived from the 1:10,000 regional topographic map (Lucchesi et al. 2014); (v) annual glaciological campaigns carried out since 1927 by the CGI surveyors (www.glaciologia.it); and (vi) publications, historical documents, photos, images and maps coming from thematic archives and databases (IGM, CGI, Italian Alpine Club, CNR-IRPI, Nigrelli et al. 2013).

Glaciological data contained in the sources (i) to (iv) were acquired in a digital format, checked, and then used for our data analyses; data contained in the archives (v) and (vi) were considered only for comparison and validation purposes, as they are unevenly distributed in time and space, or they give just a qualitative information.

On the basis of the available data, we identified five time steps (ts) covering a span of about 150 years for which the glaciological information is sufficiently complete for the entire study area: ts1, end of the LIA in the Italian Alps, around 1850, corresponding to the end of the first half of the XIX century (Orombelli 2011); ts2, beginning of the 20th century (1925–1934, depending

on the data of each IGM topographic maps); ts3, 1957–1958 (according to the year of the surveys for the Italian glacier inventory, CNR-CGI 1961); ts4, 1983; ts5, 2005–2007 (according to the year of the orthophotos of the Comunità Montana Valle Orco, produced in 2005 by Alifoto-Torino available for the OSV and LV, and the orthophotos, produced in 2006 to 2007, accessible online on the Portale Cartografico Nazionale (Italian National Cartographic Web Portal, www.pcn.minambiente.it).

The glaciological parameters calculated for the studied glaciers and for each time step are the following:

- i) Area (A): planimetric projection of the glacier surface. For the ts4, we used the values reported in the inventory “Catasto Secchieri”. For the other time steps, we drew the corresponding glacier polygons in a GIS and then calculated their surface. Only the planimetric value of the areas were taken into account because of the coarse-resolution of the digital terrain model available for the study area (DTM, 50 m grid) and its year of production (1991). In addition, topographic data related to the different time steps were not available so that any attempt to convert the projected glacial areas into surface area would prove too unreliable.
- ii) Minimum elevation (E_{min}): lowest point of the glaciers usually corresponding to the altitude of the glacier front. For the ts3 and ts4, we used the values reported in the corresponding inventories. For ts1, ts2, and ts5, we derived the data from the topographic maps. For the most recent time steps, the measurements of the annual CGI glaciological campaigns are also available. Nevertheless, we opted for using the data reported in the inventories, because those of the annual glaciological campaigns are discontinuous for the examined area and are affected by seasonal variations.
- iii) Maximum elevation (E_{max}): indicates the elevation of the highest point of the glacier. For the ts3 and ts4, we considered the values reported in the corresponding inventories; for the ts1, ts2, and ts5, we obtained the data from the topographic maps.

Comparative analysis of data derived by different sources point out some inconsistencies related to data quality and degree of detail which mainly depend on the purpose and method with which glaciological information was gathered and represented over time. Some of the main inconsistencies, and how they have been addressed for the purpose of this work, are as follows: (a) the criteria that have been used to select the bodies to be inventoried and to classify them are not homogeneous for all the inventories: some inventories include glacial bodies that are defined and archived as “glacierets,” “snowfields,” “extinct glaciers,” “ice plates,” or “ice cones”. These bodies were considered for our work only if it was possible to assess, based on the descriptive information provided by the authors of the inventory,

Table 1 Main parameters of the glaciers related to the five Alpine sectors considered in this study for each time step (ts): *OSV* Orco and Soana Valleys, *LV* Lanzo Valley, *SV* Susa Valley, *PVV* Po and Varaita Valleys, *SGV* Stura di Demonte and Gesso Valleys

Alpine sector	ts	Glaciers		Total glacier area	
		(No.)	(%)	(km ²)	(%)
OSV	1	36	100	23.12	100
	2	29	81	15.94	69
	3	24	67	11.07	48
	4	19	53	11.11	48
	5	18	50	6.72	29
LV	1	20	100	15.92	100
	2	19	95	12.40	78
	3	18	90	6.77	42
	4	19	95	8.12	51
	5	17	85	3.83	24
SV	1	9	100	4.61	100
	2	7	78	3.18	69
	3	4	44	1.20	26
	4	2	22	0.71	15
	5	1	11	0.09	2
PVV	1	11	100	1.52	100
	2	11	100	1.08	71
	3	9	82	0.60	39
	4	5	45	0.53	35
	5	4	36	0.13	9
SGV	1	20	100	3.27	100
	2	10	50	1.30	40
	3	6	30	0.22	7
	4	4	20	0.56	17
	5	0	0	0	0
Total	1	96	100	48.45	100
	2	76	79	33.94	70
	3	61	64	19.86	41
	4	45	47	20.48	42
	5	40	42	10.77	22

the presence of ice, regardless of whether or not it showed evidences of movement. In addition, some glaciers defined as “glacierets” in ts3 or ts4 were surveyed and/or measured afterwards as glaciers. In these cases, the data related to the “glacieret” have been used for the present study (Cadreghe, Pian Gias, Bonneval, Losa-62, and Becca di Gay glaciers); (b) sometimes, we found obvious errors of transcription or calculation of the morphometric parameters (e.g., maximum and minimum elevation were inverted; some numbers were missing). In these cases, if possible, we corrected the errors through observation of the morphological context or comparison with other available data; (c) in several cases, the numerical values of glacier area listed in the CGI Inventory do not agree with those of the glacier areas

drawn on the attached maps. In order to improve data accuracy, the glacier outlines reported in the individual forms have been redrawn, and their surface computed through the GIS functions. In the present work, we used the area values recalculated in this way; (d) in the “Catasto Secchieri” inventory, only glaciers of at least 0.05 km² were considered. The inventory included also glacierets with a snow permanence of 2–3 years or more. The inventory considered glacierets next to a main glacier as part of the latter and glacierets not in continuity with a main glacier as independent body. In the first case, we used to total value (glacier plus glacieret area) in the inventory, as these cases are not very frequent and we used only cumulative data of glacier surface. In the second case, we considered the glacierets for our work only if they were inventoried as glaciers in the following time steps.

For performing data analysis, we considered first all available data for any glacier and any time step and the cumulative data for each Alpine sector (Table 1).

The number of glaciers changes from one time step to another: a glacier inventoried in ts1 or ts2 might have fragmented into two or more bodies in the following time step (e.g., Pian Gias and Collarin, Mulinet, Levanne Orientale glaciers), or might have disappeared. Since only a few glaciers underwent fragmentation in the period 1850–1950s, we decided to consider the effective number of glaciers for ts1, ts2, and ts3. However, in the following decades, glaciers shrank and fragmented considerably. In order to facilitate the understanding of how the number of glaciers has changed over time for ts4 and ts5, we took as reference the glacial bodies inventoried by CGI in the 1950s (CNR-CGI 1961). A glacier inventoried as a single body in ts3, which in the 2000s is fragmented into two or more bodies, will still be considered a single unit in counting glaciers of the ts5 (glacier outlines in the 2000s and their eventual fragmentation into separate ice masses is reported in Lucchesi et al. 2014). In a few cases for some time steps, two contiguous glaciers were inventoried together as a single body (Geri Ovest and Est, Goi and Noaschetta, Colle dell’Ape and Punta Ceresole, Vallanta inferiore and Cadreghe, Colle Noaschetta Est and Ovest, Coolidge Inferiore and Superiore glaciers). In these cases, we used the value of the overall area and counted the glaciers as separate bodies.

In a second phase, we selected the glaciers with data sets covering the entire time interval considered for our study (1850 to 2007) and assessed data accuracy. For this purpose, we assigned to each data set an index of reliability ranging between 0 and 3 (0, no reliability; 1, low reliability; 2, sufficient reliability; 3, good reliability). This information is available in the Appendix. The reliability index was assigned according to the following criteria:

- i) type of glacial body (0, extinct glacier; 1, glacieret; 2, probable glacier; 3, certain glacier);
- ii) visibility conditions from the aerial photos as reported by the Authors of the inventory (0, insufficient; 1, sufficient; 2, good; 3, very good);

Table 2 Main parameters of the selected glaciers. For the SGV Alpine sector, there are no selected glaciers related to all the periods

Alpine sector	ts	TA		Emax (m a.s.l.)	Emin (m a.s.l.)
		(km ²)	(%)		
OSV (18)	1	18.34	100	3421	2746
	2	14.15	77	3407	2899
	3	10.62	58	3295	2960
	4	10.80	59	3244	2884
	5	6.72	37	3328	2998
LV (17)	1	14.07	100	3380	2680
	2	11.48	82	3351	2781
	3	6.75	48	3252	2832
	4	7.79	55	3322	2800
	5	3.83	27	3276	2928
SV (1)	1	1.75	100	3290	2700
	2	1.29	74	3180	2720
	3	0.67	38	3100	2900
	4	0.50	29	3200	2790
	5	0.09	5	3200	3010
PVV (4)	1	0.62	100	3436	2926
	2	0.57	92	3588	2935
	3	0.23	37	3320	3045
	4	0.30	48	3193	2980
	5	0.13	21	3215	3040
Total (40)	1	34.78	100	3403	2739
	2	27.49	79	3399	2853
	3	18.27	56	3358	2915
	4	19.39	56	3240	2864
	5	10.77	31	3292	2973

For each Alpine sector, the columns report the following, from left to right: the name of the alpine sector (OSV, LV, SV, PVV); the number of selected glaciers related to all the periods (in round bracket); the time step (ts); the total glacier area (TA, in km² and in percentage); the maximum and minimum mean elevation (Emax and Emin, respectively)

iii) accuracy of the data reported in the inventory, inferred from authors' comments or from the morphological context (0, insufficient; 1, sufficient; 2, good; 3, very good).

All the 40 glaciers still existing in 2000s (Appendix) displayed a mean reliability index of the related data sets ≥ 2 and were thus considered reliable for our purposes of data analysis (Table 2).

3.2 Climate data

For the purposes of this work, we analyzed data sets of mean monthly maximum air temperature (Tmax), mean monthly minimum air temperature (Tmin), monthly total precipitation (Ptot), and the number of days per month with precipitation (Pd) recorded from the most representative land-based Weather Stations (WS) in the five Alpine sectors listed in Table 3. The

climate data have been extracted from the daily and monthly digital and paper archives of the official source (ARPA Piemonte 2014a; HISTALP 2014; UIMP 1913–1994). The method used for climate data analysis is as follows:

- Step 1—identification of the most representative WS with respect to the location of the examined glacial areas. Analysis of the data information (metadata) and of the measurements recorded from these stations. Metadata are fundamental for correcting and interpreting historical and instrumental data. Their analysis allowed determination of data consistency, quality, and homogeneity and choice of the best WS suitable for our purposes. This step is crucial because the Italian official weather station network has different characteristics with respect to three different time periods: in the first period (from the early 1900s to the 40s), the number of stations located in the mountainous areas of the Po river basin was poor, and the observations were made with manual methods and basic instrumentation (maximum-minimum thermometers, pluviometers, manual snow depth measurements); in the second period (from the 50s to the 80s), the number of stations located in mountainous areas increased and the instrumentation changed from manual to semi-automatic (thermo-hygrographs, rain-snow gauges); in the third period (from the 80s to today), the number of stations remained constant compared to the previous period, and data acquisition is made by semi-automatic instrumentation and by Automatic Weather Stations.
- Step 2—choice of the best WS, collection, and digitalization of the data sets. The data sets used in this work do not include the data collected during the first period (from the early 1900s to the 40s) because the metadata analysis has shown that their quality is not good and that many data are missing. The WS chosen for this work are listed in Table 3.
- Step 3—data processing, validation, and quality control of the monthly time-series related to the WS, to reveal potential discontinuities, technical errors, jumps, outliers, or trends due to instrument drift. The objective of validation and quality control procedures (QC) is to verify whether a reported data value is representative of what was intended to be measured and has not been contaminated by unrelated factors. A first QC on the daily precipitation and temperatures was performed by the corporate bodies owning the data before their official publication in the meteorological annals. For this QC, it is not always possible to know the method used. For this reason, a second QC has been performed by the authors, on the thirty-two monthly time-series (four data sets for eight weather stations). The methodology adopted for this QC is a combination of a control by a skilled human analyst and computer programs that generate lists of potential errors, presented to the analyst for further actions (WMO 2004, 2011; Aguilar et al. 2003). Considering the good

Table 3 Main characteristics of the weather stations related to each Alpine sector and to two external areas (EA, data from HISTALP Project)

Alpine sector	No. and station name	Elevation (m a.s.l.)	Location		Obs. period Years	Nt Years	Np Years
			Lat. N	Long. E			
OSV	1. Lago di Valsoera	2365	45°29'10"	07°23'38"	1959÷2012	54 (0)	54 (0)
OSV	2. Ceresole Reale	1579	45°25'48"	07°14'40"	1950÷2012	63 (0)	63 (0)
LV	3. Lago Dietro la Torre	2370	45°15'29"	07°09'54"	1951÷2012	30 (5)	55 (7)
LV	4. Malciaussia	1800	45°12'31"	07°08'58"	1951÷2012	58 (0)	61 (1)
SV	5. Rochemolles	1960	45°07'51"	06°45'54"	1951÷2012	57 (5)	30 (0)
PVV	6. Crissolo	1422	44°42'07"	07°09'17"	1951÷2011	30 (11)	48 (13)
PVV	7. Lago Castello	1589	44°36'50"	07°03'04"	1951÷2012	60 (2)	58 (4)
SGV	8. Lago Piastra	950	44°13'40"	07°23'23"	1951÷2012	41 (4)	56 (6)
EA	9. Aosta	544	45°43'48"	07°18'00"	1841÷2008	168 (0)	nd
EA	10. Cuneo	536	44°24'00"	07°32'24"	1877÷2008	132 (0)	132 (0)

Nt and Np are the numbers of sampled years, respectively, for temperature (t) and precipitation (p) datasets (years of missing values are reported in round bracket) *nd* no data

quality of the original series, we deemed it unnecessary to fill in small gaps encountered during data homogenization and interpolation. As reported in Nigrelli and Collimedaglia (2012), when processing long time-series of climate data collected from weather stations located in alpine environments, real historic series with some small corrections and inhomogeneity are better than non-real series homogenized by comparison with reference series, geographically distant from the study area.

– Step 4—statistical analysis applied to the seasonal (DJF, winter; MAM, spring; JJA, summer; SON, autumn; NM, snow season, from November to March; OM, season with more rainfall, from October to May) and annual (year) time-series. For each single series, the statistical characteristics have been calculated, the trend test (linear regression model, Mann-Kendall correlation test) has been performed, and the standardized anomaly index has been calculated. The linear regression model ($y=a+bx$) was used to calculate the increase or decrease over time (x) of the variable (y) examined, expressed in units per year.

The Mann-Kendall test (MK) is a rank-based, non-parametric test for verifying trend significance. Its advantage is that it is distribution-free and does not assume any special form for the distribution function of the data, including censored and missing data. The null hypothesis (H_0) is that a sample of data ordered chronologically is independent and identically distributed (Sneyers 1990). This test is largely used to assess the significance of trends in hydro-meteorological time series (Yue et al. 2002).

The standardized anomaly index (SAI) is a dimensionless index obtained from the difference between a datum and the mean of a sample, divided by the standard deviation: $SAI=(x_n - x_a)/St. dev.$, where x_n is the mean value of the parameter under consideration (for example the mean annual maximum air

temperature for the year “ n ”); x_a is the sample mean (the mean annual maximum air temperature of the time-series); and St.dev. is the standard deviation of the sample. SAI values near zero indicate a temperature near the mean value, while those substantially above or below zero indicate relatively warm or cold conditions. Values between -1 and 1 (within standard deviation) are considered as normal; values in the ranges -2 to -1 and 1 to 2 indicate a moderate anomaly; values in the ranges -3 to -2 and 2 to 3 indicate a strong anomaly; and those between -4 to -3 and 3 to 4 an exceptional anomaly.

For the WS 1 to 8, these statistical tests were applied to the full period of each time-series and to two subtime-series; spanning, respectively, the 1950s to 1980 (<1980) and 1981 to the end of observation period (1981>). The year 1980 was used to divide the entire time-series into two parts because after this year, in the European Alps, negative annual mass balance prevail, contrary to the previous years (Zemp et al. 2008). We considered it appropriate to split the time-series into two parts corresponding to periods during which the European glaciers showed a clearly different behavior. Climate data analysis was performed using dedicated and free open source software (Stepanek 2006).

4 Results and discussion

In this section, we first report the results of the analysis of glacier data and then of climate data. We conclude discussing the results of the combined analysis of glaciological and climate datasets.

4.1 Glacier changes

The complete series of glaciological data for each glacier of the study area and for the five time steps is reported in Appendix. Table 1 offers a synthetic view of glacier change over time in

the five Alpine sectors. From these data, some considerations can be drawn.

- i) At the end of LIA (about 1850), 96 glaciers existed covering an overall area of 48.45 km², ranging in size from 0.03 km² (Sella Glacier) to 3.99 km² (Noaschetta Glacier).
In the 2000s, only 40 of the 59 glaciers existing in the 1950s survived, even though some of them were fragmented and/or showed little sign of activity. These 40 glaciers were preserved in four of the five Alpine sectors as follows: 18 glaciers in OSV, 17 in the LV, 1 in the SV, and 4 in the PVV. In the SGV, no glaciers inventoried in the 1980s survived to present time. Glacier area in the 2000s ranged between 0.01 and about 1.5 km²: the largest were the Noaschetta-Goi Glacier (1.45 km²) and the Nel Centrale and Occidentale Glacier (1.43 km²) in the OSV.
- ii) From the end of LIA to the 2000s, the number of glaciers decreased by 58 %. The number of glaciers has progressively decreased in all the Alpine valleys. The only exception is the LV sector, where during ts4, there was a slight increase in the number of glaciers. The LV shows the lowest reduction in the number of glaciers (−15 %) from ts1 to ts5, while SGV has the highest one (−100 %); glaciers in SGV can be considered completely extinct in the 2000s. Comparing these data with those of the adjoining French Alps, a greater reduction in the number of glaciers for the Italian side can be observed. Not considering the fragmentation that affected many glaciers from 1967 to 1971 to 2006–2009, the number of glaciers decreased by 16 % in the French Alps (Gardent et al. 2014).
- iii) The total area covered by glaciers decreased from ts1 to ts5 in all the considered Alpine sectors; the overall glaciated area decreased from 48.45 km² to 10.77 km², a reduction of 78 %. The magnitude of glacier shrinkage increases from North to South, varying from 71 % in OSV to 100 % in the SGV. Some glacier advances are recorded for ts4 (3 % compared to ts3). This was particularly marked for the LV and the SGV. These results agree with the general trend of glacier shrinkage recorded in the GAR from the end of LIA to the 2000s, but the percentage of area reduction is higher compared to other parts of the world: −50 % in the European Alps (Zemp et al. 2008), −20 % in Eurasia and Asia (Bolch 2007; Su and Shi 2002), −49 % in New Zealand (Hoelzle et al. 2007), and −25 % in North America (Fountain et al. 2006; Luckman 2000). A reduction in the same range affected the adjoining Aosta Valley, where glacial area has decreased by about 60 % during the last 150 years (Curtaz et al. 2014). The slight temporary increase of the number of glaciers recorded in LV during ts4 and of the total area recorded in OSV, LV, and SGV is in accordance with the general glacier readvance observed in the

Central and Western Italian Alps (Pelfini and Smiraglia 1988; Ajassa 1998) and in other parts of the European Alps (Zemp et al. 2008).

Table 2 synthesizes the changes of surface, and of maximum and minimum elevation, occurred between 1850 and the 2000s of the glaciers selected for the comparative analysis with climate data (see § 3.1), indicated by a (s) in Appendix. Comparison of these data with those reported in Table 1 allows assessment of the representativeness of the sample of selected glaciers with respect to the ensemble of glaciers in the area. The selected glaciers represent 42 % of the LIA glaciers of the study area, but account for 72 % of the total glaciated area at the end of the LIA.

The mean Emax and Emin were respectively 3403 m and 2739 m at the end of the LIA. The highest values of Emax were found in PVV (3436 m) and OSV (3,421 m), while the lowest elevations of Emin were of glaciers of the SV (2680 m) and SGV (2700 m). From ts1 to ts5, a general decrease in Emax and an increase in Emin can be recognized (about 90–220 m and 110–310 m, respectively). Only for ts4 a general, slight decrease of the Emin is recorded in the study area, reaching a maximum of 110 m in the SV.

From ts4 to ts5, the mean upward shift of the Emin is 131 m on average, while the Emax variation ranges between +84 m to −46 m. The shifts of Emax and Emin were generally stronger than the ones recorded in the Eastern Alps where from ts4 to ts5, an upward shift of the Emin of 53 m on average and secondarily, a lowering of Emax of 27 m on average were recorded (Carturan et al. 2013). Data are instead comparable with those recorded for the alpine glaciers of New Zealand, where a rise of Emed of about 94 m was observed in the last century (Chinn 1996).

Table 4 reports the rate of glacier retreat in the five Alpine sectors for the different time steps. The highest magnitude of glacier shrinkage was from ts4 to ts5 (mean shrinkage 3.1 %/year), while it showed a slight glacier advance from ts3 to ts4 (mean growth 0.9 %/year), particularly in the SGV (+5.9 %/year) and in the LV (+0.8 %/year). The highest rate of glacier shrinkage occurred in the SGV from ts4 to ts5 (−4.3 %/year); the lowest in the LV from ts1 to ts2 (−0.3 %/year). The slight advance recorded from ts3 to ts4 in the study area is in accordance with the worldwide increase or decrease in the retreat rate remarked between the 1950s and 1990 (Patzelt 1985; Wood 1988) which affected 85 % of the Italian glaciers (Citterio et al. 2007; Diolaiuti et al. 2011). In the Bavarian Alps, from 1971 to 1979, a maximum area increase of about +6.6 %/year can be inferred from data provided by Hagg et al. (2012). The rate of glacier shrinkage from ts4 to ts5 is comparable to those observed in the Vanoise and Ecrins Massifs of the French Alps (Gardent et al. 2014) and in the Lombardy Italian Alps, where the rate of areal decrease ranges between 1.9 and 4.7 %/year, according to the size class of the glaciers (Diolaiuti et al. 2011, 2012a).

Table 4 Change in the total glacial area (%/year) in the five Alpine sectors, related to four time-intervals (ts1–ts2, ts2–ts3, ts3–ts4, ts4–ts5)

Alpine sector	ts1–ts2	ts2–ts3	ts3–ts4	ts4–ts5
OSV	-0.4	-1.0	+0.01	-1.7
LV	-0.3	-1.4	+0.8	-2.3
SV	-0.4	-1.9	-1.6	-3.8
PVV	-0.4	-1.4	-0.5	-3.2
SGV	-0.8	-2.6	+5.9	-4.3

4.2 Trends in climate data

Regarding climate data, our study has yielded the following main results:

- i) During the period 1950 to 2012, temperatures show significant warming trends while precipitation shows no clear signal yet. This is in agreement with the findings of other studies carried out in the GAR (Ciccarelli et al. 2008; HISTALP 2014);
- ii) Positive trends for temperature are found on the entire time-series, concerning both Tmax and Tmin;
- iii) Positive trends of temperature found on the entire time-series cover all the considered temporal aggregations (annual, seasonal, NM, and OM);
- iv) Tests performed on the several time periods reveal that after 1980, the number of positive trends in temperature has increased, particularly Tmin.

In the MK test applied to the entire time-series (Table 5), results from WS 1 and WS 2 (Lago di Valsoera and Ceresole Reale, respectively) are very similar to each other, as are those of the WS 3 and WS 4 (Lago Dietro la Torre and Malciaussia respectively). In the first case, there are positive trends for Tmax (with positive trends also for Tmin in spring and summer), while in the second case, there are positive trends for Tmin. For the WS 1, there is a negative trend in Pd time-series during the periods of DJF, SON, NM, and Year. For the WS 2, there is a negative trend in Pd time-series during the periods OM and Year. We found positive trends also on all series of Tmax and Tmin related to WS 5 (Rochemolles). The positive and negative trends observed for WS 6 (Crissolo) are unclear and need further study, except for the positive annual trend, related to Tmax and Pd. The results for WS 7 (Lago Castello) showed no statistically significant trend for any Tmax and Tmin series, except for the winter season, where an increase in Tmax was detected. It is important to note the results obtained for WS 7 and WS 8 are similar to those obtained for the same area, with different methods by other authors (Terzago et al. 2013).

With regard to the MK test applied to the two parts of the entire time-series (Table 6), the most significant results have been found for temperatures. Annual trends on Tmax was found

Table 5 Trend analysis of the mean monthly maximum air temperature (Tmax, °C/year), mean monthly minimum air temperature (Tmin, °C/year), monthly total precipitation (Ptot, mm/year), and the number of days per month with precipitation (Pd, days number/year), from weather stations used in this study and for the entire time-series

Station No.	DJF	MAM	JJA	SON	NM	OM	Year
1Tmax	<i>0.08</i>	<i>0.03</i>	<i>0.04</i>	<i>0.06</i>	<i>0.07</i>	<i>0.06</i>	<i>0.05</i>
1Tmin	0.03	<i>0.05</i>	<i>0.05</i>	0.02	<i>0.04</i>	<i>0.04</i>	<i>0.04</i>
1Ptot	-2.91	-0.34	1.84	-1.41	-4.43	-4.87	-2.73
1Pd	-0.29	-0.05	0.04	-0.14	-0.47	-0.46	-0.45
2Tmax	<i>0.04</i>	<i>0.04</i>	<i>0.04</i>	<i>0.04</i>	<i>0.05</i>	<i>0.04</i>	<i>0.04</i>
2Tmin	0.01	<i>0.01</i>	<i>0.02</i>	0.01	0.00	0.00	0.00
2Ptot	-0.28	1.80	0.62	1.21	-0.17	1.44	3.74
2Pd	-0.08	0.00	-0.01	-0.04	-0.14	-0.12	-0.14
3Tmax	0.06	0.05	0.01	0.03	0.06	0.04	0.04
3Tmin	<i>0.15</i>	<i>0.20</i>	<i>0.18</i>	<i>0.14</i>	<i>0.15</i>	<i>0.16</i>	<i>0.16</i>
3Ptot	-1.16	0.09	-0.64	-1.94	-2.04	-3.09	-3.94
3Pd	-0.14	0.02	0.00	-0.06	-0.22	-0.13	-0.16
4Tmax	0.03	0.00	<i>0.03</i>	0.01	0.03	0.02	0.02
4Tmin	<i>0.09</i>	<i>0.09</i>	<i>0.08</i>	<i>0.07</i>	<i>0.09</i>	<i>0.09</i>	<i>0.08</i>
4Ptot	-0.89	1.37	0.21	-0.22	-1.05	-0.33	1.08
4Pd	-0.05	0.11	0.02	0.03	-0.02	0.08	0.13
5Tmax	<i>0.07</i>	<i>0.05</i>	<i>0.04</i>	<i>0.05</i>	<i>0.06</i>	<i>0.06</i>	<i>0.05</i>
5Tmin	<i>0.03</i>	<i>0.06</i>	<i>0.07</i>	<i>0.05</i>	<i>0.03</i>	<i>0.05</i>	<i>0.06</i>
5Ptot	-2.81	-1.12	-1.06	-1.73	-2.76	-3.94	-5.37
5Pd	-0.26	-0.19	0.01	-0.17	-0.33	-0.53	-0.50
6Tmax	0.05	<i>0.08</i>	0.04	<i>0.05</i>	0.04	<i>0.06</i>	<i>0.05</i>
6Tmin	0.03	<i>0.04</i>	-0.05	0.01	0.03	<i>0.04</i>	0.00
6Ptot	0.36	1.05	0.86	-1.46	-0.67	-0.45	2.77
6Pd	0.07	<i>0.17</i>	<i>0.24</i>	0.10	0.12	<i>0.27</i>	<i>0.64</i>
7Tmax	<i>0.03</i>	0.02	0.01	0.00	<i>0.03</i>	<i>0.02</i>	0.01
7Tmin	0.02	0.01	0.00	-0.02	0.02	0.00	0.00
7Ptot	-1.03	0.35	-0.25	-0.22	-1.21	-0.86	-1.02
7Pd	0.02	0.09	-0.01	0.02	0.04	0.15	0.17
8Tmax	-0.04	0.01	-0.01	-0.05	-0.02	-0.02	-0.02
8Tmin	<i>0.04</i>	<i>0.08</i>	<i>0.05</i>	<i>0.03</i>	<i>0.05</i>	<i>0.05</i>	<i>0.05</i>
8Ptot	-1.82	-1.60	-0.31	-0.66	-3.35	-4.65	-5.42
8Pd	0.00	0.12	0.08	-0.02	0.03	0.07	0.14

DJF, winter; MAM, spring; JJA, summer; SON, autumn; NM, snow season (from November to March); OM, season with more rainfall (from October to May); Year, calendar year; italic values indicate a 95 % significance level for the Mann-Kendall correlation tests

for WS 1 (<1980 and 1981> periods), for WS 2 (<1980 period), and for WS 5 (1981> period). All WS showed positive trends related to annual Tmin in the second period (1981>); these trends were not found in the first period (<1980). Other positive trends on Tmin were found for WS 1, 2, 3, 4, 5, and 7 in the MAM and JJA seasons for the 1981> period. For this type of test, precipitation show some slight but clear signs in three stations; for the WS 1, WS 2 and WS 4, there are some positive trend in the first period and negative trend in the second period.

Table 6 Trend analysis of the mean monthly maximum air temperature (T_{max} , °C/year), mean monthly minimum air temperature (T_{min} , °C/year), monthly total precipitation (Ptot, mm/year), and the number of days per month with precipitation (Pd, days number/year), from the weather stations used in this study and for the two parts of the entire time-series (subtime-series): from the beginning of the datasets from 1980 (<1980), and from 1981 to the end of the datasets (1981>)

Station No.	DJF		MAM		JJA		SON		NM		OM		Year	
	<1980	1981>	<1980	1981>	<1980	1981>	<1980	1981>	<1980	1981>	<1980	1981>	<1980	1981>
1Tmax	0.07	<i>0.11</i>	0.10	<i>0.06</i>	<i>0.21</i>	-0.04	<i>0.17</i>	0.03	0.09	<i>0.10</i>	0.09	<i>0.08</i>	<i>0.14</i>	<i>0.04</i>
1Tmin	-0.03	0.08	-0.10	<i>0.13</i>	-0.12	<i>0.11</i>	-0.08	<i>0.08</i>	-0.02	<i>0.09</i>	-0.05	<i>0.11</i>	-0.08	<i>0.10</i>
1Ptot	2.36	-2.00	0.07	-4.68	0.45	0.00	-7.26	-5.59	0.88	-1.15	1.68	-8.38	-4.99	-11.94
1Pd	-0.28	-0.19	-0.15	-0.14	0.01	0.20	-0.66	-0.03	-0.79	-0.17	-0.84	-0.35	-1.21	-0.14
2Tmax	<i>0.09</i>	<i>0.07</i>	<i>0.06</i>	0.03	<i>0.09</i>	-0.01	<i>0.09</i>	0.04	<i>0.09</i>	<i>0.06</i>	<i>0.08</i>	<i>0.05</i>	<i>0.08</i>	0.02
2Tmin	0.04	0.02	-0.01	<i>0.10</i>	0.00	<i>0.06</i>	0.01	<i>0.04</i>	0.03	<i>0.05</i>	0.01	<i>0.07</i>	0.01	<i>0.05</i>
2Ptot	<i>5.18</i>	-0.40	6.04	-3.99	-0.37	2.54	2.00	3.66	<i>7.08</i>	<i>3.63</i>	<i>14.18</i>	1.20	<i>12.40</i>	3.07
2Pd	0.19	-0.02	0.18	-0.06	-0.15	0.14	-0.16	-0.08	0.22	0.07	0.31	-0.21	0.01	0.01
3Tmax	nd	0.02	nd	0.00	nd	-0.01	nd	0.02	nd	0.02	nd	0.01	nd	0.00
3Tmin	nd	<i>0.14</i>	nd	<i>0.19</i>	nd	<i>0.18</i>	nd	<i>0.14</i>	nd	<i>0.15</i>	nd	<i>0.17</i>	nd	<i>0.15</i>
3Ptot	2.90	-0.51	1.68	-0.25	-2.13	2.93	0.18	1.77	4.37	3.65	7.98	-1.16	0.96	3.41
3Pd	0.21	-0.11	0.11	0.00	-0.10	0.13	-0.14	-0.06	0.24	-0.07	0.32	-0.26	-0.13	0.00
4Tmax	0.04	-0.03	0.02	-0.05	0.00	0.00	0.06	-0.04	0.06	-0.05	0.05	-0.04	0.03	-0.03
4Tmin	0.12	<i>0.09</i>	0.03	<i>0.16</i>	0.00	<i>0.14</i>	0.06	<i>0.09</i>	<i>0.11</i>	<i>0.10</i>	<i>0.08</i>	<i>0.12</i>	0.05	<i>0.12</i>
4Ptot	<i>5.24</i>	-3.40	1.82	-4.22	-1.01	2.47	-3.63	2.41	4.76	-0.17	5.80	-4.24	-0.23	-0.46
4Pd	0.19	0.03	0.03	0.01	0.05	0.14	-0.07	0.02	0.20	0.26	0.19	0.11	0.07	0.36
5Tmax	-0.02	0.03	-0.02	<i>0.11</i>	-0.04	<i>0.07</i>	0.00	0.02	-0.02	0.03	-0.04	<i>0.06</i>	-0.01	<i>0.06</i>
5Tmin	0.05	0.04	<i>0.09</i>	<i>0.06</i>	0.04	<i>0.04</i>	0.05	0.00	0.05	0.04	0.06	<i>0.05</i>	0.05	<i>0.04</i>
5Ptot	nd	-2.81	nd	-1.12	nd	-1.06	nd	-1.73	nd	-2.76	nd	-3.94	nd	-5.37
5Pd	nd	-0.26	nd	-0.19	nd	0.01	nd	-0.17	nd	-0.33	nd	-0.53	nd	-0.50
6Tmax	nd	nd	-0.13	<i>0.05</i>	-0.23	0.00	0.07	0.03	nd	0.04	nd	0.04	nd	0.02
6Tmin	nd	nd	0.04	0.00	0.20	-0.06	0.02	0.00	nd	0.00	nd	0.01	nd	-0.01
6Ptot	4.39	0.75	4.22	-6.44	0.42	-1.47	-2.04	2.58	4.62	1.26	4.00	-1.95	-2.68	0.59
6Pd	0.34	0.24	<i>0.85</i>	-0.20	<i>0.55</i>	0.02	0.26	0.31	0.46	0.41	<i>1.29</i>	0.24	<i>2.21</i>	0.49
7Tmax	<i>0.09</i>	0.02	0.00	<i>0.06</i>	0.01	0.03	0.05	0.00	<i>0.08</i>	0.03	0.04	0.03	0.03	0.02
7Tmin	-0.04	<i>0.08</i>	-0.09	<i>0.12</i>	-0.12	<i>0.10</i>	-0.11	<i>0.05</i>	-0.06	<i>0.09</i>	-0.08	<i>0.09</i>	-0.09	<i>0.09</i>
7Ptot	3.54	-1.65	-1.69	-2.86	0.38	-0.01	-2.49	1.95	2.02	-0.63	-0.85	-3.18	-3.12	-1.47
7Pd	0.19	0.05	-0.05	0.02	0.08	0.05	-0.23	0.04	0.14	0.14	-0.07	0.20	-0.22	0.35
8Tmax	-0.03	-0.06	-0.02	0.00	0.00	-0.03	-0.13	-0.06	-0.01	-0.05	-0.11	-0.03	-0.03	-0.03
8Tmin	0.02	0.03	0.01	<i>0.07</i>	-0.07	<i>0.05</i>	-0.10	0.02	0.00	0.04	-0.03	<i>0.04</i>	-0.03	<i>0.04</i>
8Ptot	3.55	1.15	0.61	-1.94	-0.01	-0.28	-6.36	<i>5.10</i>	0.76	6.78	1.10	5.87	-2.93	4.30
8Pd	0.27	0.02	0.26	0.02	0.23	-0.23	-0.19	0.02	0.37	0.20	0.59	0.15	0.40	-0.09

DJF, winter; MAM, spring; JJA, summer; SON, autumn; NM, snow season (from November to March); OM, season with more rainfall (from October to May); Year, calendar year; italic values indicate a 95 % significance level for the Mann-Kendall correlation tests

nd no data

Annual temperature (T_{max} and T_{min}) and precipitation (Ptot) variability in the five Alpine sectors from the 1950s to 2012 are shown in Fig. 2 as a standardized anomaly index (SAI). In general, the trends of temperature increase, while precipitation remains relatively stable around the 0 value. The variability of the T_{max} shows, in recent years, an increase only in the OSV, SV, and PVV Alpine sectors, with the values of SAI not exceeding 1, therefore not very significant. However, variability of the T_{max}

in the SGV Alpine sector shows a clear decrease from 2001. The variability of T_{min} shows the most interesting and noticeable trend. In general, this parameter starts to increase at the beginning of the 1990s. This increase becomes more evident in recent years, especially in LV and SGV. For this parameter, it seems the oscillation takes values more pronounced from North to South.

The absence of temperature data for the period 1850 to 1950 does not allow us to know the relationship between

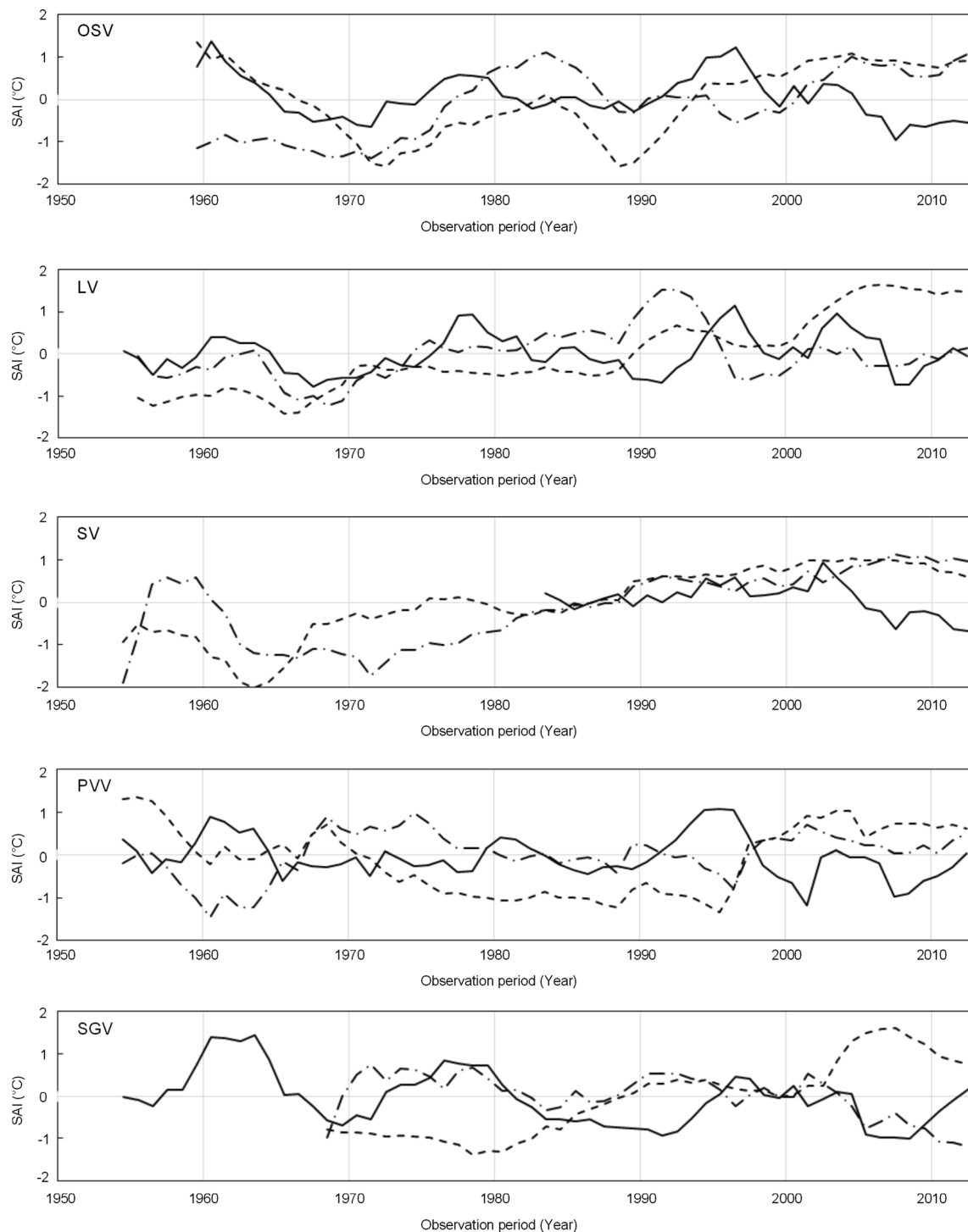


Fig. 2 Temperature and precipitation variability in the five Alpine sectors, from 50s to 2012. Standardized anomaly index (SAI) related to the mean annual maximum temperature (*dash-dot line*), mean annual minimum temperature (*dashed line*) and total annual precipitation

(*solid line*). All signals have been passed through a 5-year moving average. For the SV Alpine sector, the precipitation data availability is starting from 1983

climate trends and glacier evolution for that period. To try to fill this gap, we used two datasets of homogenized series processed in the framework of the HISTALP Project, representative of the Northwestern Italian Alps (HISTALP 2014). These series are the mean monthly temperature data for the

Aosta (WS 9) and Cuneo (WS 10) station. The comparison between homogenized and non-homogenized climatic series is not correct from a statistical point of view, but our goal was and to provide an estimate of the temperature variability associated with glacial areas fluctuations in the period 1850

to 1950. The mean temperature series (T_{mean}) of the WS 9 and WS 10 were divided into 30-year time periods (5 subseries): 1860 to 1889; 1890 to 1919; 1920 to 1949; 1950 to 1980; 1981 to 2008. For these five subseries the same processing performed on the T_{max} and T_{min} series of the WS 1 to 8 were carried out. The results obtained from these analyses are not reported here but are in agreement with results obtained for the other WS 1 to 8, confirming a significant increase in mean temperature during spring and summer for the period 1980 to 2008 ($0.09^{\circ}/\text{year}$ in the spring and $0.07^{\circ}/\text{year}$ in the summer for Aosta; $0.08^{\circ}/\text{year}$ in the spring and $0.07^{\circ}/\text{year}$ in the summer for Cuneo). For the period 1950 to 1980, a significant decrease of the mean temperatures in the summer at the Cuneo Station ($-0.04^{\circ}/\text{year}$) was detected, while for all the other subseries, there are no statistically significant trends.

4.3 Climate data applied to glacier variations

Based on the analysis of glaciological and climatic data, we identified the total glaciated area and spring and summer

temperature variations as the most significant parameters for a joint analysis.

Figure 3 shows the total glaciated area of each Alpine sector, for each time step, in relation with the corresponding variation of the maximum and minimum temperatures of spring and summer.

The decline of glaciated areas over time is evident, even though occurring at different rates in the five Alpine sectors. Furthermore, this areal reduction increases from ts4 to ts5 (-1.7 , -2.3 , -3.8 , -3.2 , and -4.3 $\%/ \text{year}$, respectively, for the OSV, LV, SV, PVV, and SGV Alpine section, see Table 4).

Our results are consistent with glacier retreat observed in these Alpine sectors by other authors and in the other sectors of the Southwestern region of the GAR (Bonanno et al. 2014; D'Agata et al. 2014; Diolaiuti et al. 2012b).

Figure 3 shows a significant decrease in minimum temperatures from 1950 to 1980. This is associated with a slight increase in glacial areas recorded in two Alpine sectors (LV and PVV). From 1981, the graph shows a significant increase in minimum temperatures, more evident than shown by

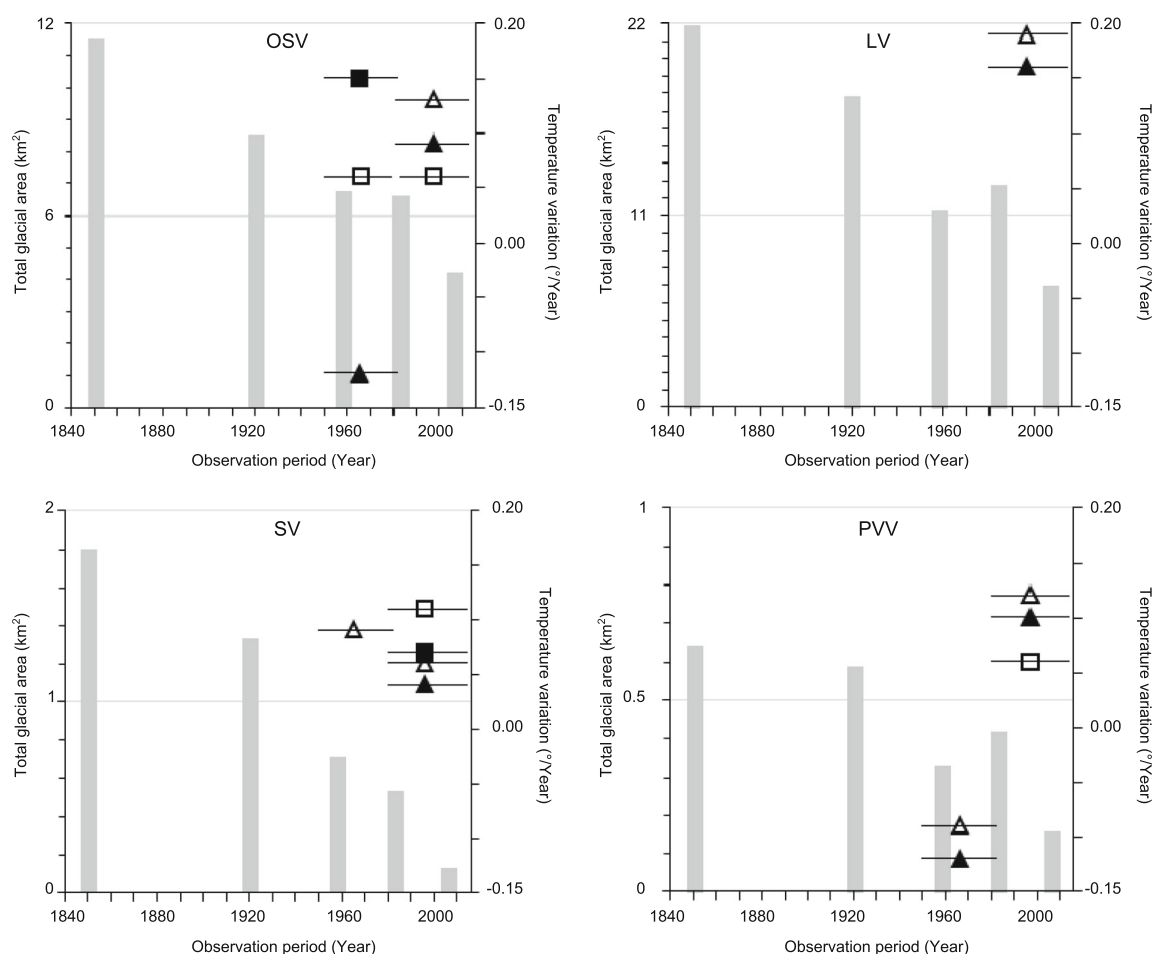


Fig. 3 Alpine glaciers evolution in Northwestern Italy, since the second half of the nineteenth century, in relation with recent and significant maximum (T_{max}) and minimum (T_{min}) temperatures increase ($^{\circ}\text{C}/\text{year}$), observed in spring (MAM) and in summer (JJA), for the two

periods examined: 1951 to 1980 and 1981 to 2012. *Gray bars* total area of selected glaciers (km^2), *white square* T_{maxMAM} , *white triangle* T_{minMAM} , *black circle* T_{maxJJA} , *black triangle* T_{minJJA}

maximum temperatures. In addition, the minimum temperatures of spring record the highest annual increases (0.12–0.20 °C/year). The increase in minimum and maximum temperatures (especially in spring but also in summer) can thus be considered the cause of the increase in the rate of decline of glacial areas since the 1980s. Acceleration in glacier shrinkage was also observed in the French Alps located to the West and near of our study area by other authors (Gardent et al. 2014).

As discussed in section 3.2, precipitation trends are much less clear than temperature signals. Nevertheless, in a few cases, they are statistically significant, with positive and negative values, respectively, for the <1980 and 1981> periods (see Table 6). In these cases, the precipitation signal is in agreement with the direction of glacier change: for example, in the OSV, positive values of the P_{tot} were observed at WS 2 during DJF, NM, OM, and year of the <1980 period, while negative values of the P_{tot} were observed at WS 1 during DJF, MAM, and OM of the 1981> period. In the LV, positive values of the P_{tot} were observed at WS 4 during DJF of the <1980 period, while negative values of the P_{tot} were observed at WS 4 during DJF of the 1981> period. In these cases, we can speculate that glacier change was driven by a combination of temperature and precipitation variation. In the other cases, temperature has to be considered the only climate factor causing glacier evolution.

For this reason, the increase of minimum temperatures in spring and in summer does not seem to be the only cause of reduction in glacial areas after the LIA, but seem, rather, to accelerate a trend already present. In some cases, these trends are also accelerated by a decrease in solid precipitation falling from October to May. These results are consistent with significant decrease of snow depth observed in Northwestern Italy during this period of time by Terzago et al. (2013).

5 Conclusions

In this work, we have analyzed the climate variability and glacier evolution from the Little Ice Age to the 2010s in the Western Italian Alps. In this sector of the Southwestern region of the GAR, the retreat of the glaciers was almost continuous from the peak of the LIA on, and many glaciers are now extinct. These latter are those already small in size during the LIA and/or located at the lowest latitudes, e.g., in the Stura di Demonte and Gesso Valleys (SGV) where climatic conditions are most affected by the influence of warm Mediterranean regimes. After the LIA, the climate showed significant variability. Both minimum and maximum temperatures increased, this increase being significant from 1980 onwards. The retreat of the glaciers, which began long before the 1980s, however, is evidence that temperature increase was only one of its causes. The information provided by precipitation data analysis is still unclear and does not provide statistically significant trends in the study area. However, we

can say that changes in this parameter, which often are toward a decline, help to define the trend of glaciers analyzed.

This work also responds to a need for knowledge concerning the main characteristics of each glacier, and its evolution in time, from ts1 to ts5. For this reason, the series of morphometric parameters published in Appendix, constitutes the first comprehensive, multitemporal collection of data on the glaciers of this area, which is supplied to the scientific community in order to increase the availability of glaciological data to be used for different purposes.

We hope this study will contribute to increased knowledge of the relationships between climate and glacier evolution in the Greater Alpine Region.

Acknowledgments This work was carried out within the activities of the Project of Interest NextData (www.nextdataproject.it). We wish to thank Dr. Anna Maria Gaffodio, Dr. Paola Bassi (ARPA Piemonte) and Ing. Daniele Cat Berro (Società Meteorologica Subalpina) for climatic data providing, and Dott. Giovanni Mortara for sharing his glaciological expertise of the study area.

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