

Temperature changes in the North-Western Italian Alps from 1961 to 2010

Fiorella Acquavotta · Simona Fratianni · Diego Garzena

Received: 9 October 2013 / Accepted: 7 November 2014 / Published online: 28 November 2014
© Springer-Verlag Wien 2014

Abstract The aim of this study was to identify any possible temperature changes within the last 50 years in the North-Western Italian Alps by examining data from 16 high-altitude weather stations in the period 1961–2010. The daily temperature time series were collected, digitized and subjected to a historical research to individuate discontinuities and retrieve metadata. We also carried out the data quality control and the homogenization which allowed the climatic indices trend detection. The analysis of the temperature values showed an increase in temperature, particularly at high-altitudes sites. In fact, the stations located above 1600 m asl revealed a rise in temperatures and a decrease in the number of cold periods. For the maximum temperatures, greater increases in spring and winter have been observed, for minimum temperatures in the summer. These trends confirm that climate change is occurring in an environment particularly sensitive to temperature changes, especially during the season of snow accumulation and vegetative growth. These results may be important for policy makers to define the best adaptation strategies in order to protect one of the most sensitive environments such as mountains.

1 Introduction

Recent global climate changes have been investigated and described in many studies (Alexander et al. 2006; Aguilar et al. 2005; Barriopedro et al. 2006; Bradley et al. 1987; Dos Santos et al. 2010; Karl et al. 1993; Liu and Chen 2000).

The global average warming in the twentieth century has been estimated to be at about 0.6 °C (Jones and Moberg 2003). Luterbacher et al. (2004) analysed the trends and extremes of European temperature, with a dataset from the 1500 to 2000, and found that the twentieth century was the warmest since 1500 with a strong warming trend of 0.08 ± 0.03 °C per decade and that the nine warmest European years on record have occurred since 1989 ($\Delta T = +1.3$ °C). In Italy, an increase of approximately 1 °C has been measured over the last 50 years of the twentieth century (Brunetti et al. 2000a; Toreti and Desiato 2007, 2008).

As reported by Lionello (2012), the temperature in the Mediterranean are characterized by high spatial complexity and a pronounced seasonal cycle, and they are influenced by large-scale atmospheric circulation land-sea interactions and local processes (Terzago et al. 2013; Trigo et al. 2006; Xoplaki et al. 2003). In the past six decades, in the Mediterranean areas, an overall warming trend has been reported (Brunet et al. 2007; Brunetti et al. 2009; Kafle and Bruins 2009; Toreti et al. 2010). The recent upward tendency, started in the western Mediterranean followed by increases in the eastern part (Miranda and Tome 2009; Tayanç et al. 2009), shows a trend particularly pronounced in summer, while several locations do not show a significant trend in winter (El Kenawy et al. 2009; Toreti et al. 2010), although on a centennial timescale, trends are highly significant in all seasons (Brunetti et al. 2009).

The whole Mediterranean region has been considered sensitive to actual (Giorgi 2006) and future climate changes, as established by many studies through the use of climate model simulations (Giorgi and Lionello 2008; Lionello et al.

F. Acquavotta · S. Fratianni · D. Garzena (✉)
Dipartimento di Scienze della Terra, Università di Torino,
via Valperga Caluso 35, 10125 Torino, Italy
e-mail: diego.garzena@unito.it

F. Acquavotta
e-mail: fiorella.acquavotta@unito.it

S. Fratianni
e-mail: simona.fratianni@unito.it

S. Fratianni
Centro interdipartimentale sui rischi naturali in ambiente montano e collinare, NatRisk, via Leonardo da Vinci 44, 10095 Grugliasco, TO, Italy

2006a,b; Ulbrich et al. 2006). In this context, for its geomorphological characteristics, the Alpine region is one of the most sensitive environments to climate change (Knoche 2011). Since 1996, the IPCC has underlined the need to understand and predict the effects of climate change in mountainous regions through monitoring, experimental studies and modelling. A change in the alpine climate regimes can, in fact, influence winter precipitation (IPCC 2007; Valt et al. 2006), and the persistence of the snow cover can lead to impacts of considerable magnitude (Ronchi and Loglisci 2008) on river systems and on the socio-economic structures (Fazzini et al. 2004) of the populations that live in the mountains and valleys (Beniston et al. 1997; Hill Clarvis et al. 2013). The positive trend observed for winter temperatures is closely linked to the reduced snow cover that has been observed in recent years in the Alps (Jacobson et al. 2004; Rebetez and Reinhard 2008; Serquet et al. 2013).

In terms of climate research, the European Alps constitute a region of high potential (Auer et al. 2007; Barontini et al. 2009; Böhm et al. 2001; Brunetti et al. 2009; Casty et al. 2005; Durand et al. 2009; Matulla et al. 2005; Van der Schrier et al. 2007). The Alpine region is, in fact, a transition zone between three climatic zones (the Atlantic Ocean, the Mediterranean Sea and the European mainland; see for instance: Bartolini et al. 2009; Jungo and Beniston 2001) to which the effects of altitude have been added (Auer et al. 2005).

Among the numerous studies on the Swiss Alps, Beniston and Rebetez (1996) and Beniston et al. (1997) showed that there is a correlation between the variation in temperature and altitude. Diaz and Bradley (1997) analyse elevational differences in long-term temperature trends, using high-elevation station records from various locations over the world, and found that the warming of the surface temperature is strongest for high-altitude site. In more recent studies, it has been observed that the greatest temperature changes have been recorded in the cold seasons, when the anomalies of the daily maximum can reach 20 °C or more (e.g. December 17th 2005, Fratianni et al. 2009), compared to the increment of 10 °C observed for the summer heat waves (Beniston 2005).

The data measured at global level do not allow us to have a clear picture of the ongoing work at a local scale. Jungo and Beniston (2001) through a study on the Swiss Alps were able to identify an increase in temperatures of up to 2 °C between 1901 and 2000. However, there are many gaps in Italy, compared to other neighbouring states, although some national studies have been conducted (Brunetti et al. 2006; Brunetti et al. 2001a; Brunetti et al. 2000a, b; Cacciamani et al. 2001; Corti et al. 2009; Maugeri and Nanni 1998; Toreti and Desiato 2007, 2008).

The Alpine region has been the subject of many studies, but more broad-spectrum studies have been conducted over the eastern Alps (Bocchiola and Diolaiuti 2010; Brugnara et al. 2012; Brunetti et al. 2001b; Di Piazza and Eccel 2012; Fazzini

and Gaddo 2003) than over the western Alps (Ciccarelli et al. 2008; Mercalli et al. 2008). The recent studies in this area are mostly of a very localized nature, such as Acquotta and Fratianni (2013), which deals with an analysis of rainfall time series in Piedmont, or that of ARPA Piemonte (2012), on the climatological atlas of Verbano CusioOssola and, or of Fratianni and Motta (2002) that consider the Susa valley, or Nigrelli and Collimedaglia (2012) pertaining to the Alpe Devero and Domodossola meteorological stations, or still those of Biancotti et al. (1998 and 2005), Valt et al. (2008 and 2006) and Terzago et al. (2012 and 2010), Acquotta et al. (2013b) and Fratianni et al. (2014) which are focused on the analysis of snow depth and snow precipitation on Italian Alps.

Considering other indicators of global climate change, Harris et al. (2003) on a study of permafrost explain that “reacts sensitively to changes in atmospheric temperature” and still Harris et al. (2003) analysing further studies highlight (Dramis et al. 1995; Haeberli 1992; Haeberli et al. 1997; Haeberli and Beniston 1998; Harris et al. 2001a,b) “it is predicted that degradation will lead to an increased slope instability in lower latitude mountains”.

Carturan et al. (2013) analysing the changes in area, length and volume of the glaciers in the Ortles-Cevedale group (centre-eastern Italian Alps) from the 1980s to the 2000s found links between the behaviour of glaciers (retreat) and the meteorological data series recorded at 2605 m by the Careser dam weather station. In that station, strong positive trends for both annual (0.5 °C per decade) and summer (0.6 °C per decade) temperatures were recorded. Huss (2012) evaluating the glacier mass balance in the European Alps over the twentieth century identifies a strongly negative mass balances for the 1940s and the last two decades when the average annual balance approached -1 m w.e. a^{-1} . The mean area-averaged mass balance in the European Alps is $-0.31 \pm 0.04 \text{ m w.e. a}^{-1}$ for 1900–2011 corresponding to a total ice volume change of $-96 \pm 13 \text{ km}^3$. A previous study of Haeberli (1990) relates the increase of air temperature of 0.5 to 1.0 °C which occurred in the twentieth century and correlates it with the mass loss of glaciers in the middle and low latitudes and the decrease the length of the Alpine valley glaciers.

As regards to future models and scenarios, Huss (2012) estimated an increase of the average air temperature by 2–5 °C by 2100 (relative to 1961–1990 annual average air temperature using Global Circulation Model), while the annual precipitation totals remain almost constant. His models indicate a general trend to drier conditions and warming greater than the annual average in summer. Future glacier mass balance at the scale of the European Alps is expected to show a negative trend over the next decades for all scenarios. Marzeion et al. (2012) have presented a model, to reconstruct the annual glacier surface mass balance based solely on monthly temperature and precipitation data. The source of data for temperature and precipitation used in that study was the HISTALP

dataset (Auer et al. 2007). On the scale of the whole alpine region, the study of Marzeion et al. (2012) report that the temperature slightly dominates precipitation as the driver of mass balance variability and identify a positive temperature anomaly during the winter.

In the frame of the study of the influence of the North Atlantic Oscillation (NAO) on mass balance variability of European glaciers, Marzeion and Nesje (2012), according to Reichert et al. (2001), highlight on the western Alps that the winter precipitation and temperature anomalies cause a weak anti-correlation between mass balances and NAO. While in the eastern Alps, a weak positive correlation between NAO and mass balances, in the more central and southern parts of the Alps, the lack of a precipitation signal leads to a weak anti-correlation between mass balances and NAO.

This work will deepen the existing knowledge and give an overview of climate change over the northwestern Alps. The aim of this study is focused on the temperature data analysis over the last five decades through the use of a new daily temperature time series from high-altitude meteorological stations (from 700 m to 2400 m asl). This high-quality dataset has a good temporal continuity and was recovered, digitized and then subjected to a strict quality control and homogenization to avoid any non-climatic variations that could affect the analysis. Since the mid twentieth century, the study area has been monitored by the installation of several weather stations. However, these data have yet to be used in a single study. In most cases, the development of the monitoring network has only enriched the public body data archives. This rich meteorological dataset which has been collected over the years contains a set of precious information, which, even today, not only allows one to recognize the climatic variations that have occurred in a zone, but also to cast light on the formation mechanisms of the climate and to makes future forecasts easier.

2 Geography of the North-Western Alps

The area of North-Western Italian Alps analysed in this work develops within the territories of Piedmont region. Interestingly, from South to North the Ligurian, Maritime, Cottian, Graian, Pennine and Lepontine Alps, the territory covers approximately 25,399 km² accounting for about 4.3 million inhabitants. The Alpine region is bordered by Switzerland, France and the Italian regions of Lombardy, Aosta Valley and Liguria.

The Piedmont region (Fig. 1) is made up of three geomorphological areas: mountains (Alps and Apennines), hills (Monferrato and Langhe) and plain.

The mountain area covers about 12,000 km² and includes the highest mountains in Italy and in Europe: the Monviso (3841 m asl), Rocciamelone (3538 m asl), Punta Ciaramella

(3676 m asl) and Argentera (3297 m asl). The plain covers 6450 km², including the area between the foot of the Alps and the hills of Monferrato and Langhe. The hilly area covers 6570 km² and it is composed of the hill of Turin, the Langhe and Monferrato.

Two main factors induce the thermal-pluviometric characteristics of Piedmont: the orography, the greater internal factor, and the atmospheric circulation with dry continental air flowing in from Po Valley in the east and relatively moist Mediterranean and Atlantic air coming in with north-western flows (Fратиanni et al. 2005).

3 Historical time series

This work has allowed us to recover and analyse long-term daily temperature series (covering approximately the last eight decades) of 16 high-altitude manual stations. Most of them are located close to reservoirs, made by the National Energy Authority (ENEL), for electricity exploiting. The main advantages of this weather network are the following: the high-altitude location of the stations, the availability of a complete archive of metadata and no significant changes in the environment surrounding of the stations.

For each meteorological station, we recovered the hand-made register and digitized all daily data. Since the registers also contain information on changes in the instrumentation and location, a metadata file associated with the station data file was created as well. It contains the location of the station (geographical coordinates and altitude), the nearby basin, the instrumentation and all reported changes.

The weather stations are distributed across the Piedmontese Alps, from the Maritime Alps to the Lepontine Alps, at altitudes between about 700 and 2400 m asl, representative of all Alpine sectors, with the exception of the Ligurian Alps (Fig. 1).

The longest retrieved time series are the ones of Rochemolles, Cavalli and Ceresole with data from 1926, 1930 and 1932, respectively. From 1934 to 1938, four stations began their activity and by 1961, the number of available weather stations reached 15 (Table 1). Thus, the 50-year period of activity from 1961 to 2010 was selected to perform the analyses and identify the peculiarities of the high-altitude stations in Piedmont. However, gaps affect the investigated time series also in the selected time period. The stations with the largest number of missing data (4 % of the daily records) are Rochemolles and Rosone followed by Devero with 2 % of missing days.

The station Piastra was added to cover the Maritime Alps area and increase the number of stations between 700 and 1000 m asl. Their data record started in 1968, and to remember that this station does not cover the entire period, Piastra will hereafter be identified as Piastra*.

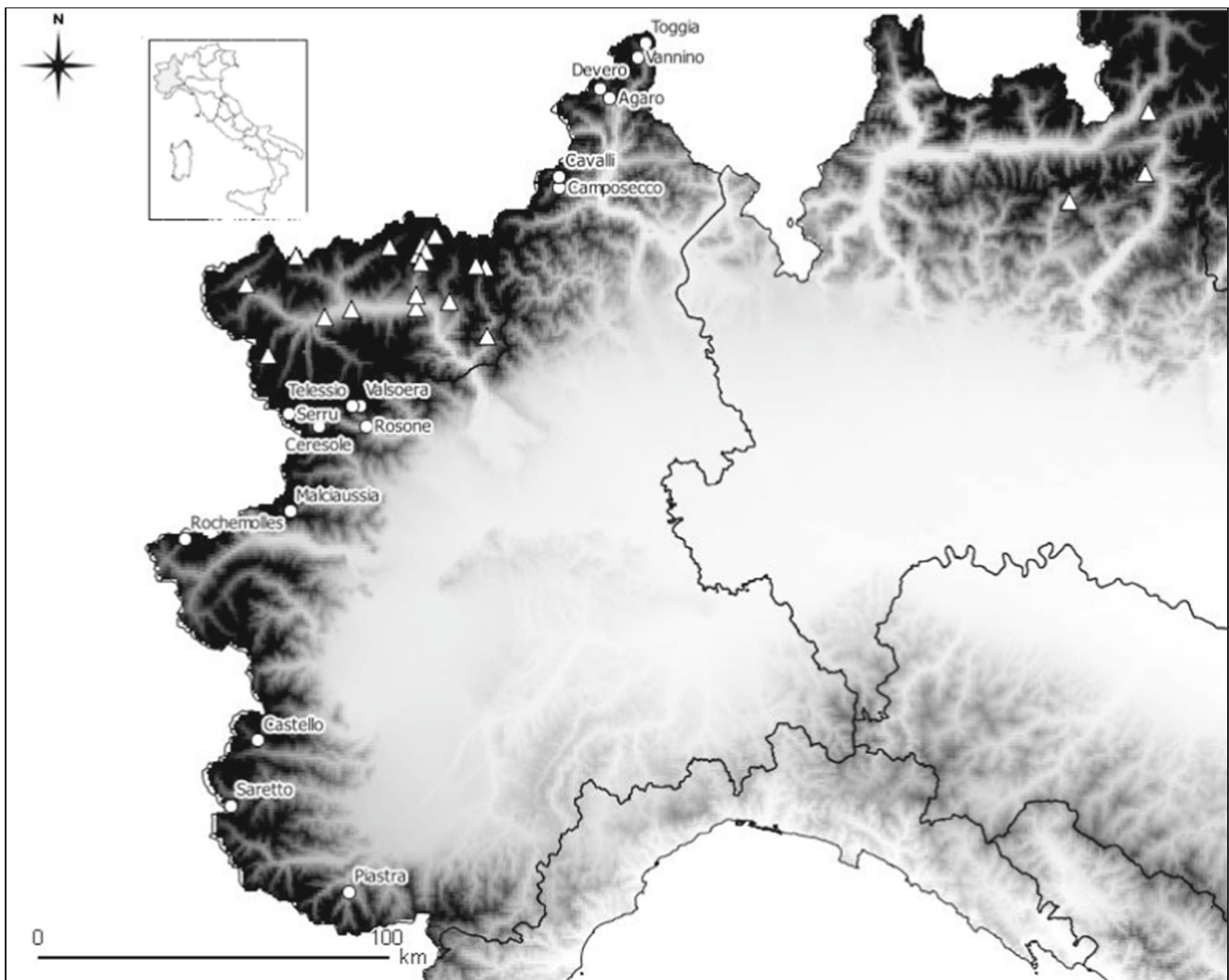


Fig 1 Study area with the meteorological stations (*dots*) and series used for the homogenization (*triangles*)

4 Methodology

The retrieved temperature data underwent quality control in order to check for any possible mistakes in the time series, for example, human errors due to digitization process or the original data registration. The data check was carried out using the software RCLimdex (Zhang and Yang 2004), which allowed us to identify data transcription errors, for example, a maximum temperature less than minimum temperature and also identified outliers in daily maximum and minimum temperatures. The outliers are daily values outside an interval; in this work, the interval, in agreement with Acquaotta et al. (2009) and Aguilar et al. (2005), is the mean plus or minus four times standard deviation of the daily value. All the values out of this range were placed in a separate file, and then we have performed another check on the data to define if any value marked was really an outlier. The check was accomplished by comparing the values with the original records, and then the consistency was verified in the range of

5 days before and after the outlier and using neighbouring stations and historical newspaper.

We used the monthly averages only if at least 80 % of the daily data was available, equal to a gap of 6 non-consecutive days (Klein Tank et al. 2002; Sneyers 1990) and for the annual averages, at least the 94 % of the daily data, equal to a gap of 20 non-consecutive days (Klein Tank and Können 2003).

Conrad and Pollak (1962) before and Peterson et al. (1998) after explain that we have a homogeneous time series when the variations are due only by variations in climate. Therefore, in order to perform the climatic analysis, the daily temperature data were subject to a homogenization process. To homogenize the variables, we have employed the SPLIDHOM method (Mestre et al. 2011; Venema et al. 2012). The test is fully based on non-parametric regression and relies on cubic smoothing spline. The use of a smoothing parameter set by means of cross-validation allows avoiding over fitting during the estimation process. The SPLIDHOM method, to be applied with good results, recommends a correlation, between

Table 1 Main characteristics of the meteorological stations

No.	Weather stations	ID	Alpine sector	Activity period	Altitude [m asl]	Coordinates	
						Longitude	Latitude
1	Lago Valsoera	Valsoera	Graian A.	1959–2010	2412	7.3957	45.4868
2	Camposecco	Camposecco	Pennine A.	1951–2010	2316	8.1169	46.0589
3	Lago Serrù	Serrù	Graian A.	1961–2010	2283	7.1356	45.4611
4	Lago Vannino	Vannino	Lepontine A.	1951–2010	2177	8.4019	46.3986
5	Toggia	Toggia	Lepontine A.	1937–2010	2165	8.4300	46.4361
6	Rochemolles	Rochemolles	Cottian A.	1926–2011	1950	6.7672	45.1317
7	Lago Pian Telesio	Telesio	Graian A.	1959–2010	1940	7.3683	45.4844
8	Malciaussia	Malciaussia	Graian A.	1937–2010	1800	7.1494	45.2086
9	Alpe Devero	Devero	Lepontine A.	1951–2010	1634	8.2611	46.3169
10	Agaro	Agaro	Pennine A.	1961–2010	1600	8.3017	46.2917
11	Lago Castello	Castello	Cottian A.	1943–2010	1589	7.0511	44.6139
12	Ceresole reale	Ceresole	Graian A.	1932–2010	1573	7.2456	45.4311
13	Acceglio Saretto	Saretto	Cottian A.	1934–2010	1540	6.9586	44.4444
14	Alpe Cavalli	Cavalli	Pennine A.	1930–2010	1500	8.1167	46.0878
15	Lago Piastra	Piastra*	Maritime A.	1968–2010	960	7.3894	44.2281
16	Rosone	Rosone	Graian A.	1938–2010	701	7.4194	45.4353

the candidate series and the reference series, possibly equal or greater than 0.8. The dataset of historical series was improved with 20 reference series from Aosta Valley and Lombardy regions, with comparable topographical features. However, for the correction of the series, only the metadata identified by historical research have been used.

The trends, of meteorological variables, TX and TN, and climate indices have been calculated for the monthly, seasonal and annual values. The trends were computed using the Theil-Sen approach (TSA) (Sen 1968; Zhang et al. 2000; Toreti and Desiato 2008). The trend is removed from the series if it is significant and the autocorrelation is computed. This process is continued until the differences in the estimates of the slope and the AR (1) (autoregressive model) in two consecutive iterations are smaller than 1 %. The Mann-Kendall test for the trend is then run on the resulting time series to compute the level of significance. TSA is preferred to the linear least square that is more vulnerable to gross error of data and has a confidential interval more sensitive to the non-normality of the distributions.

Six temperature indices (Table 2) are selected from the list of 27 core climate extreme indices defined by the expert team (ET) and its predecessor, the CCI/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) and recommended by the World Meteorological Organization-Commission for Climatology (WMO-CCL). For percentile indices (e.g. the number of days exceeding the 90th percentile of minimum temperature or maximum temperature), the methodology uses bootstrapping for calculating the base period values so there is no discontinuity in the

indices time series at the beginning or end of the base period (Zhang et al. 2005). The selected base period for the percentile indices was 1971–2000.

The standardized anomaly index (SAI) has been calculated for maximum and minimum temperatures of all the stations, using as reference period the 1971–2000. Finally, the SAI results were divided for the altitude of the stations in two groups, upper or equal to 1600 m asl and below the 1600 m asl.

5 Results

5.1 Homogenization

The database, used to homogenize the maximum and minimum temperature series for this study (Table 3), includes 17 series recorded from 1928 of Aosta Valley and 3 from 1951 of Lombardy (Fig. 1). The historical research on the Piedmont stations has highlighted averagely two breaks (Fig. 2 left). The breaks highlighted in the early twenty-first century, in most cases, are due for a change of location or instruments of the weather stations. In this period, across the 2002 and the beginning of 2003, the manual stations were replaced by automatic stations for a reorganization of the meteorological network. The second most important breaks shown by the historical research are due by a change of instruments, from a maximum and minimum thermometer to a thermograph. In some stations, Ceresole, Rosone, Agaro, Rochemolles and

Table 2 Climate indices

ID	Indicator name	Definitions	UNITS
TX	Tmax	Mean maximum value of daily maximum temp	°C
TN	Tmin	Mean minimum value of daily minimum temp	°C
TN10p	Cool nights	Percentage of days when TN<10th percentile	% Days
TX10p	Cool days	Percentage of days when TX<10th percentile	% Days
TN90p	Warm nights	Percentage of days when TN>90th percentile	% Days
TX90p	Warm days	Percentage of days when TX>90th percentile	% Days
WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX>90th percentile	Days
CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN<10th percentile	Days

Toggia were highlighted breaks due to a change in the time of instrument reading.

For every location, we have created a metadata file that shows the following: the locations of the meteorological station, the basin it belongs to, the latitude, the longitude, the altitude, the instrument type, the change of location or instrument and the operating periods. In addition, for each meteorological station, cartographical maps with different levels of detail have been drawn, while the photographic documentation completes the information.

The cartography, obtained from the Regional Technical Cartography (CTR, scale 1:10,000) and from the map of Italy (scale 1:25,000) of the Military Geographical Institute, Cartographic State Agency, shows the relative position of the stations (Fig. 2 right) (Acquaotta et al. 2013a).

For each station and for both the series, maximum and minimum temperatures, averagely, three reference stations with high correlation coefficient and a mean distance of 94 km (Table 3) were selected. For the minimum temperature the mean difference of elevation between the candidate series and reference series is equal to 370 m while for the maximum temperature is equal to 345 m (Table 3).

Before analysing the homogenized data, the difference between the original and homogenized data are discussed. Figure 3 shows the mean annual adjustment curves for maximum and minimum temperatures. The large standard deviation range (grey lines) underlines again the absolute necessity to homogenize in order to get any reasonable single-station series. Some systematic biases in the adjustment curves are evident. In the early period, from 1961 to 1979, for both the temperature series, the average of the difference series reveals a general increasing due to a change of instruments, from the thermometer to the thermograph, by a progressive technological evolution of the meteorological stations. The second step starts from 1987 when on the study area, a new meteorological network was created, belonging to ARPA Piedmont, to improve the quantity of meteorological data on the region in order to better explain the complexity of the territory for forecasting purposes. These corrections influence the trends

of minimum and maximum temperatures in the 1961–2010 period. In particular, the increase of the temperature recorded in this century is underestimate because in the cool period, 1970s years, the correction factor increases the temperature averagely of 0.5 °C for minimum temperature and 0.6 °C for maximum temperature while in the last period the factor decreases the temperature averagely of –0.1 °C for both the variables.

5.2 Average monthly temperatures

The stations located at an altitude greater than 2000 m asl measured the higher values of maximum monthly average temperature between 12.3 °C of Toggia and 15.0 °C of Serrù both in July, while the lowest, in winter, are between –0.7 °C of Camposecco and –3.5 °C of Toggia.

The lowest values are between –11.9 °C of Toggia and –9.1 °C of Camposecco and Serrù in January and February. The highest values, instead, are recorded in August, with values between 5.0 °C of Vannino and 6.4 °C of Camposecco.

The stations with altitude between 2000 and 1000 m asl measure higher values of the maximum monthly average temperature between 15.8 °C of Telessio and 21.9 °C of Saretto in July and the minimum values, between 1.1 °C of Telessio and 5.9 °C of Saretto in January and December.

The highest values of minimum monthly average temperature between 8.1 °C of Rochemolles and 11.9 °C of Castello are in July and August. In January and February, the temperatures vary between –5.3 °C of Cavalli and –10 °C of Devero. Generally, in these stations, the monthly average minimum temperature never exceeds 0 °C from November to March. In some locations, minimum temperatures below 0 °C are measured occasionally in the month of April. In these months, the temperatures vary between –2.5 °C of Devero and –0.2 °C of Cavalli (other locations with these values are Rochemolles, Telessio, Malciaussia, Agaro and Ceresole).

The stations located at an altitude less than 1000 m asl estimate a maximum monthly average temperature between 27.1 °C in August and 2.4 °C in January recorded at the station

Table 3 Relationship between candidate and reference series for minimum and maximum temperature

Stations	Altitude (m)	Mean altitude of reference stations	Mean corr coef	Number of reference stations	Mean distance (km)
Minimum temperature					
Valsoera	2412	1880	0.93	4	94
Camposecco	2316	1766	0.93	4	50
Serrù	2283	2035	0.87	2	106
Vannino	2177	1737	0.90	4	75
Toggia	2165	1176	0.79	3	113
Rochemolles	1950	1612	0.76	5	109
Telessio	1940	1564	0.93	4	61
Malciaussia	1800	1212	0.86	2	102
Devero	1634	1805	0.78	2	47
Agaro	1600	1945	0.94	4	56
Castello	1589	1601	0.79	5	140
Ceresole	1573	1550	0.86	6	74
Saretto	1540	1133	0.77	3	133
Cavalli	1500	1186	0.91	1	52
Piastra*	960	1255	0.87	2	107
Rosone	701	1227	0.85	4	56
Maximum temperature					
Valsoera	2412	2027	0.86	3	110
Camposecco	2316	1833	0.90	2	26
Serrù	2283	2212	0.83	3	144
Vannino	2177	1917	0.89	3	34
Toggia	2165	1575	0.73	2	107
Rochemolles	1950	2291	0.79	2	171
Telessio	1940	1777	0.89	3	71
Malciaussia	1800	1244	0.79	4	121
Devero	1634	2168	0.83	2	16
Agaro	1600	1819	0.89	4	48
Castello	1589	1596	0.74	5	138
Ceresole	1573	1801	0.85	2	69
Saretto	1540	1187	0.70	4	163
Cavalli	1500	1335	0.83	4	57
Piastra*	960	1303	0.75	4	123
Rosone	701	1471	0.79	3	58

of Rosone, and for minimum temperature, between 13.4 °C of Piastra* in August and -4.9 °C of Rosone in January. Values below 0 °C are measured from December to February and, only for the Rosone station, also in March.

For the maximum temperature, the difference between the lower and higher values is more pronounced at low altitudes (ΔT between 20.6 and 24.7 °C) than at higher elevations (ΔT between 13.1 and 16.8 °C). Instead for the minimum temperature, the difference between the lower and higher values is almost similar at all the altitudes (ΔT between 14.7 and 17.8 °C).

5.3 Trends and indices

We have estimated the trends of maximum and minimum temperatures on the Piedmont Alps in the last 50 years, from 1961 to 2010. The analysis highlights a significant warming tendency in most of the locations. Only in Castello station (1589 m asl), a non-significant decreasing tendency has been estimated (Table 4). The more complex behaviour of Castello station is related to the topographic characteristics of the measurement area. This is a bottom valley station, oriented NW-SE along the

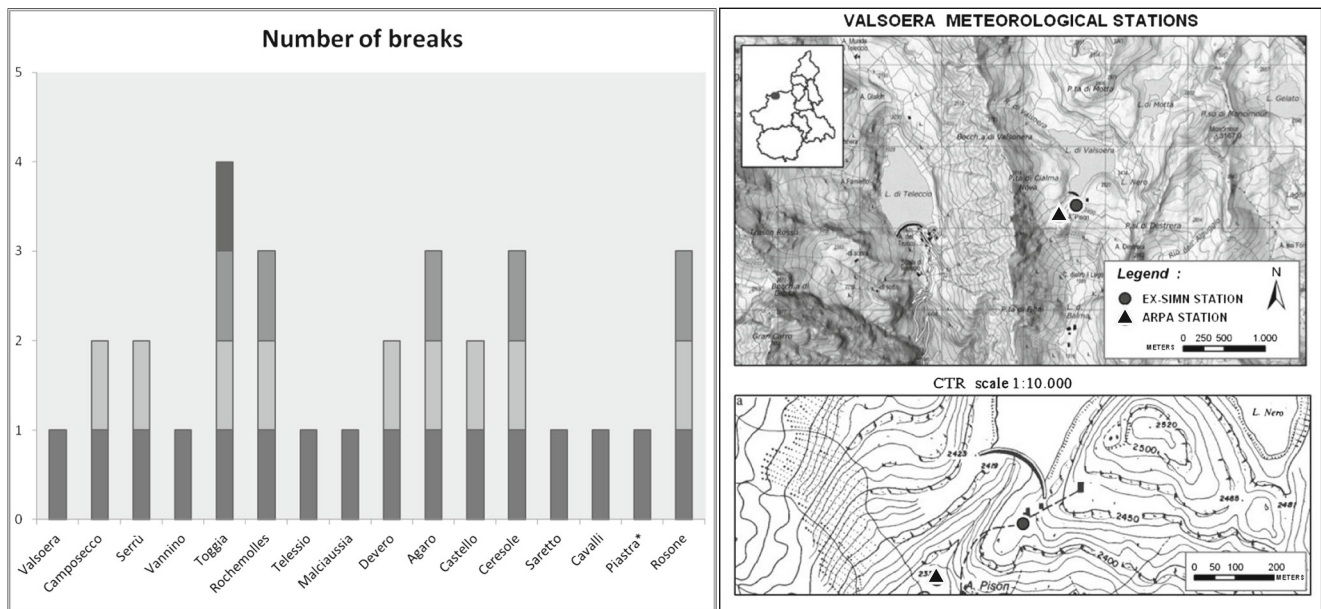


Fig 2 Left panel, number of breaks highlighted in the stations; right panel, cartographic map of a station, example of a relocation from manual station (EX-SIMN station) to automatic station (ARPA station)

direction of the prevailing winds, where the cold air tends to stagnate, especially in the evening.

Rochemolles (1950 m asl) and Valsoera (2400 m asl) stations record the highest trend, respectively, 0.072 and 0.067 °C/year of mean maximum temperature, Toggia (2165 m asl) and Vannino (2177 m asl) stations follow with, respectively, 0.038 and 0.036 °C/year. The increasing of maximum temperature was recorded in all the seasons, in the stations located at altitudes higher than 2000 m asl and lower than 1600 m, the maximum contribution is in spring (March). The stations located between 2000 and 1600 m asl record the maximum trend in winter (January).

The increase of maximum temperature is also highlighted by the climate indices TX90P and TX10P. The warm day index (TX90P) designed to detect the days with extreme maximum temperatures shows increasing and statistically

significant trends. The maximum slope (0.41 % day/year) is calculated in Valsoera followed by Rochemolles with 0.33 % day/year. Only in few locations, Camposecco, Serru, Castello and Piastra*, the trends are decreasing but not statistically significant, while in Rosone, the trend is decreasing and statistically significant (−0.17 % day/year). The warm spell index (WSDI) shows a slight increasing only for the stations with elevation under 2000 m asl. The maxima of WSDI occurred in 1964 and 2003, while the minimum values in 1973, 1980, 1984, 1992 and 1997. In some of the stations, the cold day index (TX10P) shows a decreasing trend statistically significant. The statistically significant decreasing was calculated in Toggia at the elevation of 2165 m asl (Table 4).

For the mean minimum temperature, the trends are increasing and statistically significant in most locations analysed. The highest slopes are calculated in the stations with elevation

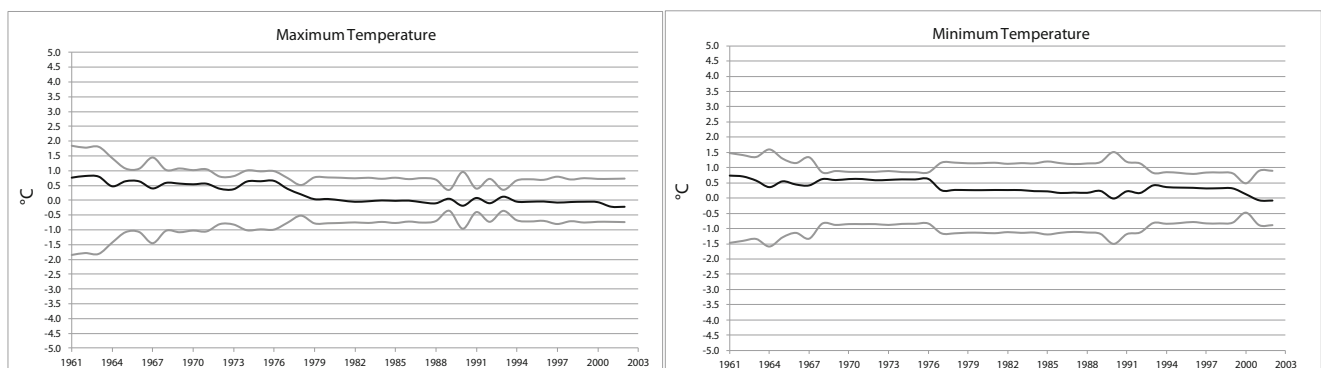


Fig 3 Adjustment curves, homogeneous minus original data, averaged over 16 locations for maximum temperature (left) and minimum temperature (right); black lines mean, grey lines the standard deviation range

Table 4 Annual estimated trends, from 1961 to 2010, for maximum (TX) and minimum (TN) temperature and the related climate indices (TX90P, TX10P, WSDI, TN90P, TN10P and CSDI)

Weather Stations	Elevation (m)	TX	TX90P	TX10P	WSDI	TN	TN90P	TN10P	CSDI
Valsoera	2412	0.067***	0.410***	-0.135	//	0.077***	0.397***	-0.170**	//
Camposecco	2316	-0.003	-0.041	-0.055	//	0.069***	0.215***	-0.355***	-0.298***
Serrù	2283	-0.002	-0.044	0.020	//	0.052*	0.301***	-0.135	//
Vannino	2177	0.036***	0.105**	-0.151***	//	0.069***	0.403***	-0.233***	-0.181***
Toggia	2165	0.038***	0.214***	-0.216***	//	0.024***	0.102**	-0.122**	-0.011
Rochemolles	1950	0.072***	0.328***	-0.162***	0.018	0.018***	0.111**	-0.155**	//
Telesio	1940	0.021	0.283***	0.050	0.018	0.034**	0.200**	-0.103	//
Malciaussia	1800	0.021	0.089	-0.079**	//	0.067***	0.348***	-0.193***	//
Devero	1634	0.005	0.188*	0.132***	0.007	0.027	0.184*	0.021	//
Agaro	1600	0.020	0.107*	-0.033	//	0.016	0.125*	-0.084	-0.010
Castello	1589	-0.006	-0.050	0.002	//	-0.039***	-0.213***	0.191***	0.101**
Ceresole	1573	0.013	0.23**	0.094	0.086	0.007	0.377*	0.071	//
Saretto	1540	0.033***	0.082	-0.171***	//	0.022**	0.099**	-0.162***	-0.030
Cavalli	1500	0.035***	0.178***	-0.051	//	0.025***	0.147***	-0.090	//
Piastra*	960	0.028***	-0.045	-0.022	//	//	0.121*	-0.160***	//
Rosone	701	-0.059***	-0.169***	0.184***	-0.083*	0.016*	0.118	-0.035	//

For each trend, we report slope and the statistical significance. The symbol double solidus means no trend

*90; **95; ***99 %

greater than 1600 m asl. Valsoera (2412 m asl) shows the maximum value (0.077 °C/year) followed by Camposecco (2316 m asl) and Vannino (2177 m asl) with 0.069 °C/year and Malciaussia (1800 m asl) with 0.067 °C/year. The increase of minimum temperature was calculated in all seasons but the higher values were recorded in summer in particular in June, while for the locations situated below 1600 m asl in spring in the month of May (Table 4).

Also, for the warm nights, TN90P, we have calculated increasing and statically significant trends exception for Castello. The higher slopes were estimated always in the stations with elevations upper 1600 m asl. The maximum trend (0.4 % day/year) was calculated in Vannino (2177 m asl) and Valsoera (2412 m asl) followed by Ceresole (1573 m asl) with 0.38 % day/year. For the high-elevation stations (upper 2000 m asl), the maximum values of warm nights were calculated in 2003, while in the other stations after 2003 in particular in 2007. For the cold waves (CSDI) and cold nights (TN10P), the trends are decreasing and statistically significant above the 2000 m asl, while for the TN10P, the greater decreases were calculated in the stations with elevations upper 1600 m asl. For both the indices, the maximum values were estimated in Camposecco (2316 m asl) (Table 4).

The spatial distribution trends of the climatic indices in Table 4 are shown in Fig. 4. The different alpine sectors do not show common climate variations. The data show increasing trends in all the sectors of the Alps, but the slopes of the regression lines are different from each other.

Homogeneous variations were identified to the different elevations as it emerged from the analysis of trends.

The trend estimates allowed to identify three ranges of elevations. From the stations with elevations at upper 2000 m asl, we have calculated a greater increasing of minimum temperature compared the maximum temperature. The estimated trend for the minimum temperature (statistical significant) is 0.06 °C/year with an increase of 2.84 °C in the analysed period. Between 1600 and 2000 m asl, the maximum and minimum temperatures highlight the same (statistically significant) increase with a trend of 0.03 °C/year, respectively, equivalent to an increase of 1.6 and 1.72 °C for the entire period. Below the 1600 m asl, the trends of maximum and minimum temperatures have different trends, respectively, a non-significative negative trend of -0.01 °C/year and a positive statistically significant trend of 0.02 °C/year (Table 5).

Upper or equal to 1600 m, the greater increase of minimum temperature was recorded in summer, while in the areas located at an altitude below 1600 m, maximum growth is measured in the spring. The maximum temperature highlights similar trends in the three altitude ranges. At upper 2000 m asl, the maximum increase was recorded in spring, between 2000 and 1600 m asl in winter and below 1600 m asl in spring.

The asymmetry observed between maximum and minimum temperature trends in North-West of Alps is consistent with similar observations deduced by other study on Alps (Beniston et al. 1997 and Beniston 2005); (Luterbacher et al. 2004) on sub-continental scale and the (IPCC 2013) on the global scale have shown that over much of the continental

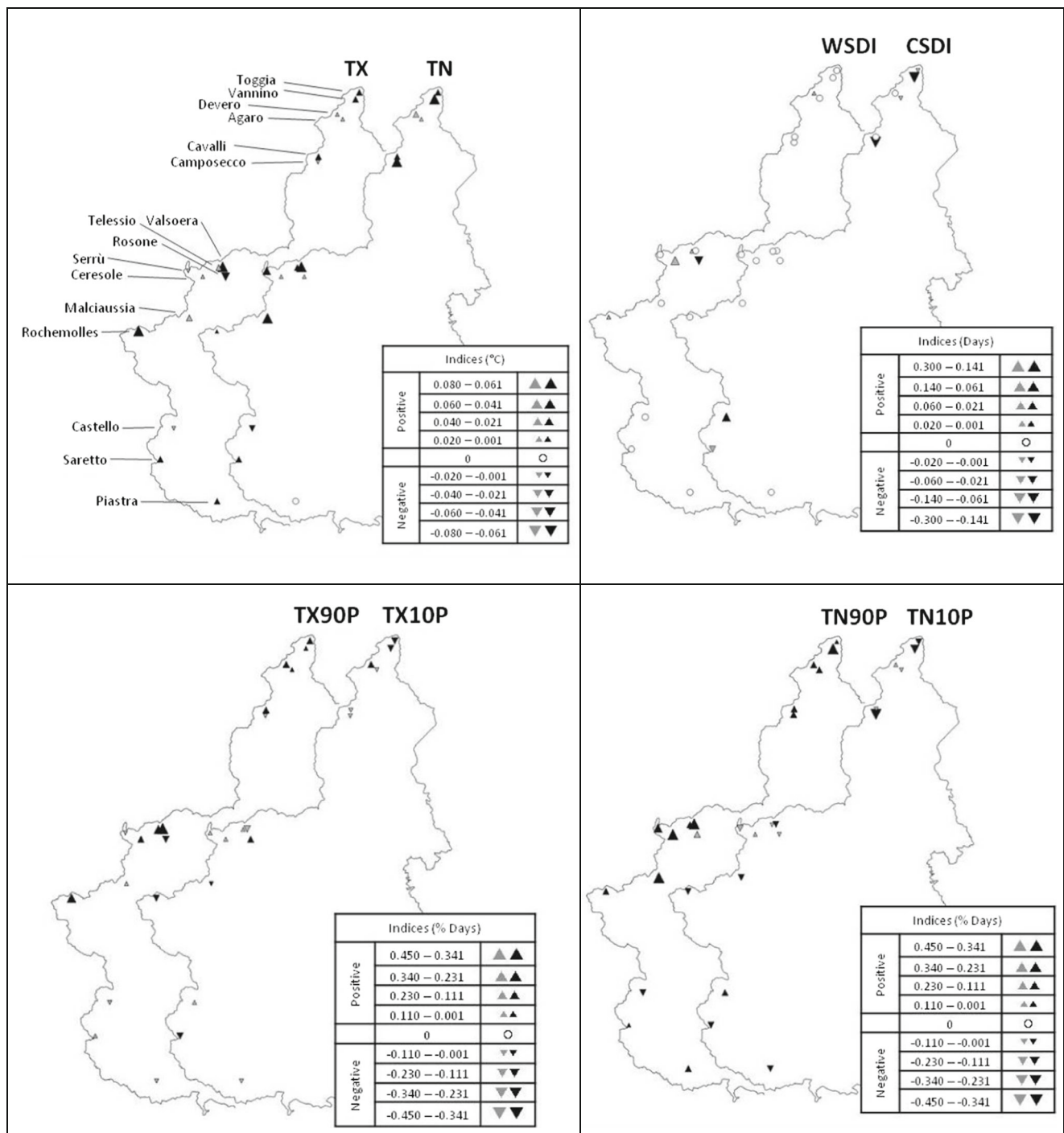


Fig 4 Spatial distribution of the temperature trend. The symbols (*black up-pointing triangle*) for positive and (*black down-pointing triangle*) negative trends, statistically significant at 90 %, while the symbols

(*white up-pointing triangle*) the positive and (*white down-pointing triangle*) the negative trends statistically non significant

land mass, minimum temperature have risen faster than the maximum temperature.

In the same study area (NW Italian Alps), Terzago et al. (2013) and Acquotta et al. (2013b) have found a decrease of snow depth in all the stations over seasonal (November–May) time scale in the period 1951–2010. The main valued

contribution for to this negative trend comes from spring when the snow depth decrease is comparable to the one registered over the complete season. Furthermore, the authors have identified that around 1500 m asl, the strength of the snow depth decrease. Besides the strongest spring snow depth reduction, the Northern stations suffer also a significant snow

Table 5 Annual estimated trends, from 1961 to 2010, for maximum (TX) and minimum (TN) temperature

Series	Trend (°C/year)	ΔT over the time period (°C)
TX	0.02***	0.75
TX≥2000 m asl	0.02***	1.24
2000<TX≤1600 m asl	0.03***	1.60
TX<1600 m asl	-0.01	-0.50
TN	0.04***	1.95
TN≥2000 m asl	0.06***	2.84
2000<TN≤1600 m asl	0.03***	1.72
TN<1600 m asl	0.02***	1.10

For each trend we report slope and statistical significant. With *** are indicated the trends significant for 99 %

depth decrease during winter months, so North Piedmontese Alps result as the most sensitive to climate change. In a future work, it may be related to the results obtained in these papers, increasing data with the continuous collection of long time series of other regions, in order to better understand the effects of climate change over the North-Western Italian Alps.

5.4 Standardized anomaly index

The standardized anomaly index (SAI) has been calculated to evaluate the trend of the maximum and minimum temperatures over the last 50 years (1961–2010), in the Piedmontese Alps. The SAI provides an immediate idea of the degree of anomaly of the behaviour of the temperature recorded in a given year compared to the behaviour of the same variable in a 30-year reference period, here 1971–2000.

The SAI series of maximum and minimum temperatures (Fig. 5) have two very similar trends. For both the variables, the trends are positive and statistically significant. For the maximum temperature, the trend can range from 0.08/10 to 0.31/10 years while for the minimum temperature from 0.12/10 to 0.36/10 years. The progressive Mann-Kendall test applied to two SAI series shows a positive trend without changes of slopes. The *u* and *u'* time series in the diagrams move parallel to each, which it has not highlighted variation on the slope of the trends.

In the first 26 years, from 1961 to 1986, the SAI series shows values lower than average except in a few years. For both maximum and minimum temperatures, the positive values are calculated only in 9 years during the 1960 and 1980s (Fig. 5).

Over the next 24 years, from 1987 to 2010, the SAI series show values higher than average in most years, indicating a progressive increase in temperatures. Minimum temperatures below zero values are calculated only in 3 years, 1991, 1996 and 2010, while for the maximum temperatures in 5 years, 1993, 1995, 1996, 1999 and 2010.

The SAI was calculated also on two altitude ranges, elevations upper or equal to 1600 m asl and elevations below 1600 m asl (Fig. 6). As the SAI calculated on all series, the trends for maximum and minimum temperatures show a positive slope and the progressive Mann-Kendall test does not highlight a change of behaviour. The maximum slope is calculated for minimum temperature (0.28–0.51 °C/10 years) following by maximum temperature with 0.19–0.41 °C/10 years. For the minimum temperature, positive values of SAI were detected from 1987 while for the maximum temperature from 1997 (Fig. 6).

In the zones with altitude below 1600 m, the SAI for the maximum temperature does not show long period with

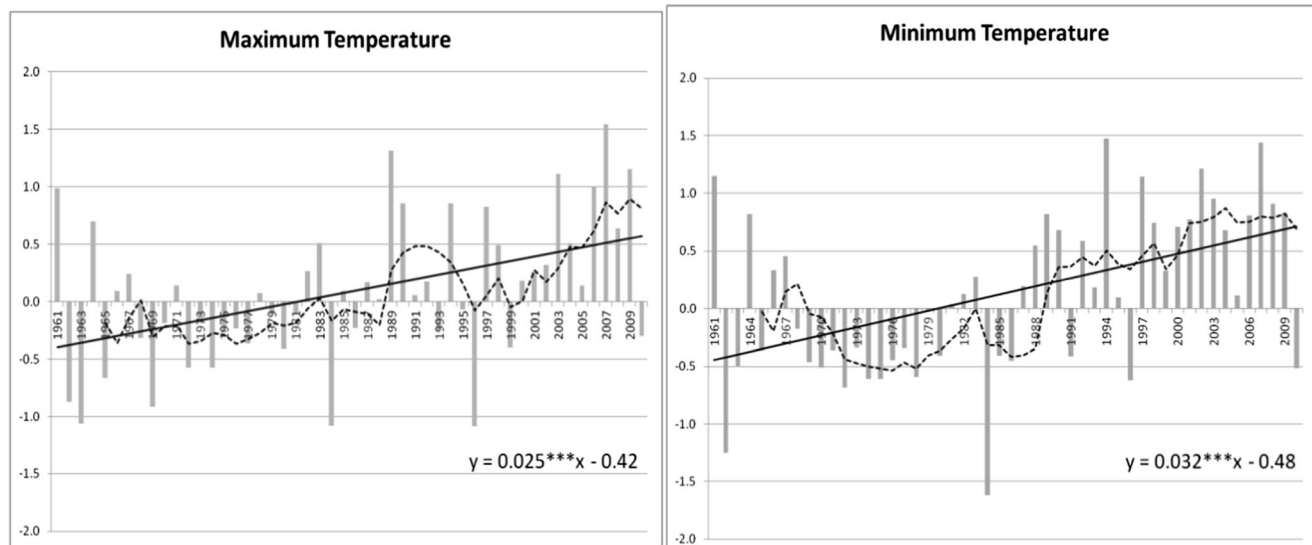


Fig 5 Left, SAI of the maximum temperature from 1961 to 2010; right, SAI of the minimum temperature from 1961 to 2010. The black line shows the linear trend; the dotted line shows the moving average on

5 years. For each trend, we report slope and the statistical significance (starred: *90, **95 and ***99 %)

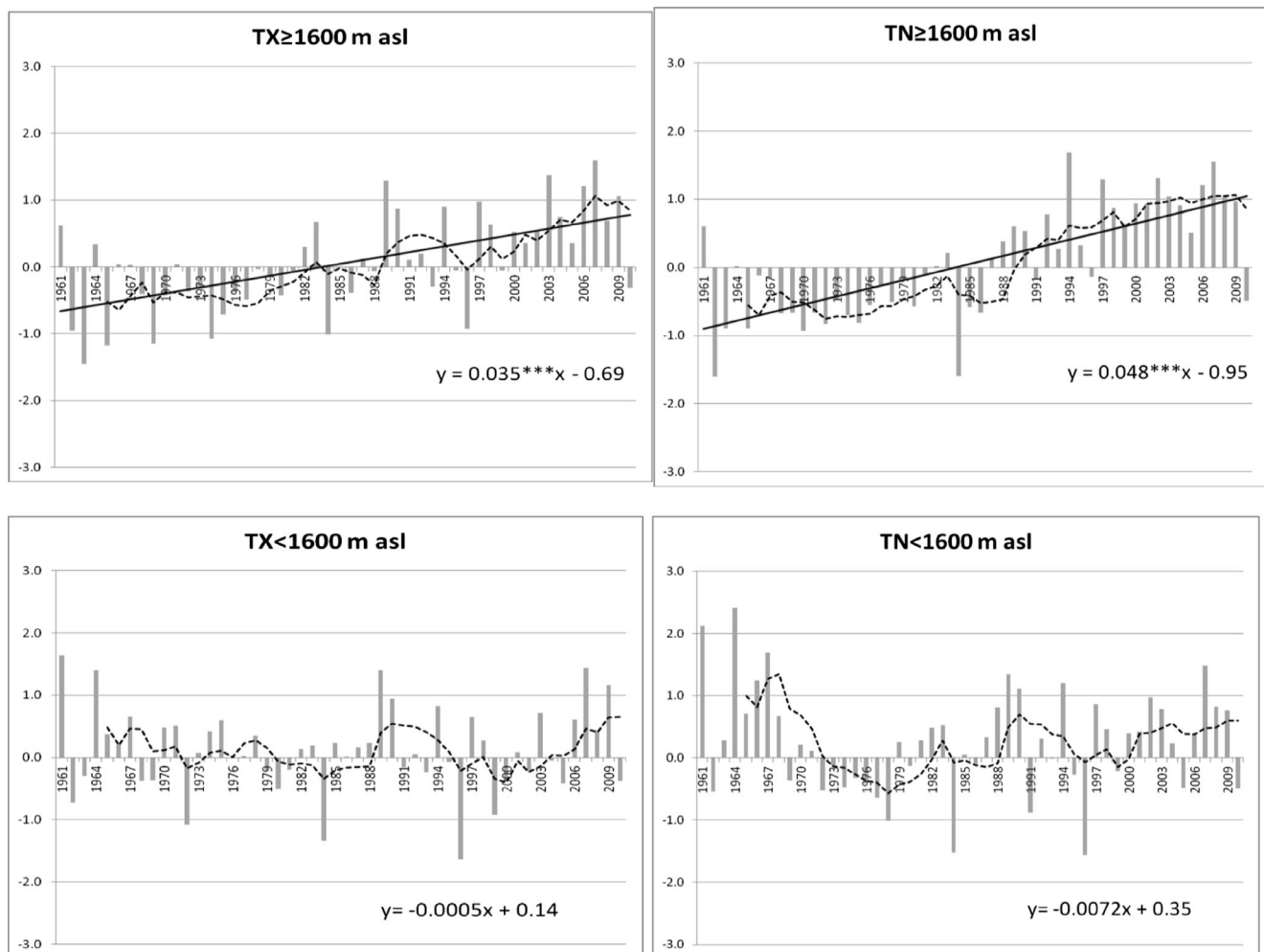


Fig 6 SAI for maximum (TX) and minimum (TN) temperature at altitude greater or equal to 1600 m (*upper*) asl and below 1600 m asl (*lower*). The *black line* shows the linear trend; the *dotted line* shows the moving

average on 5 years. For each trend, we report slope and the statistical significance (starred: *90, **95 and ***99 %)

positive or negative values. Positive values were calculated at the end of the 1960s and 1980s and in the 2000s, while negative values in the 1970s and early 1980s and at the end of the 1990s. This behaviour does not allow to calculate any trend. The u and u' time series calculated by the progressive Mann-Kendall test indicate that there is no meaningful trend and/or a sudden change (jump) in the time series except two periods, from 1980 to 1990 and from 2000 to 2010, with a positive slope.

For the minimum temperature, we can identify periods with positive SAI, from 1961 to 1969 and from 1987 to 2009, or negative SAI, from 1970 to 1986 (Fig. 6). On the entire period, from 1961 to 2010, there is no trend but the progressive Mann-Kendall identifies two periods with different behaviours, from 1961 to 1975 a negative trend and from 1976 to 2010 a positive trend. The negative trend, -0.003 °C/year, is not statistically significant while the positive trend, 0.02 °C/year, is statistically significant.

6 Conclusions

In the present study, the temperature data from 16 stations in the North-Western Italian Alps have been analysed using data between 1961 and 2010. The stations are located between 700 and 2400 m asl and have a manual observation data system. The data were therefore digitized, subjected to a quality control and finally homogenized. The climatic and trend analysis have shown different trends in temperature from station to station, according to the detection altitudes. A positive trend can be observed for the temperature at which an increase in altitude generally corresponds. The stations located above 1600 m asl, in particular, show a rise in temperatures and a decrease in cold periods. The higher trends for these stations were calculated on the minimum temperature, but for both variables, that is, the maximum and minimum temperatures, while the maximum trends were only estimated in the locations at elevations above 2000 m asl. The maximum temperature increase was 0.072 °C/year in Rochemolles

(1950 m asl), while the minimum temperature was 0.069 °C/year in Camposecco (2316 m asl). Those increases at high elevations, although of different entities due to the different location of the analysis areas, are in agreement with the studies carried out on Alpine permafrost (Haeberli and Beniston 1998; Harris et al. 2001a,b and 2003) and glaciers (Carturan et al. 2013; Haeberli 1990; Huss 2012).

Another interesting fact has emerged from the analysis of the seasonal temperatures. It can be observed that, at the high-altitude stations, the seasons that recorded the greatest changes are different for the minimum and maximum temperatures. The greatest changes for the maximum temperatures were recorded in March and January, while the greatest changes for the minimum temperatures were recorded in June. The maximum temperature analysis highlights an increasing trend in winter between 2000 and 1600 m asl. This increase at the mid altitudes could adversely affect on the tourist exploitation of the Alpine region. The rising of temperatures will be accompanied by snow losses for winter tourism and skiing season causing impacts on the socio-economic structures (Fazzini et al. 2004) of the populations that live in the mountains and valleys (Beniston et al. 1997).

Moreover, Terzago et al. (2013) outlines a significant decrease of snow depth in all the Piedmont stations over seasonal (November–May) time scale in the period 1951–2010. The main contribution to this negative trend comes from spring when the snow-depth decrease is comparable to the one registered over the complete season. Besides, the strong links between NAO and snow depth in all the measurement sites and the weaker relation with fresh snow precipitation suggest that NAO mainly controls snow depth via temperature, which affects the snow melt and the vegetative growth season.

The analysis of the climate indices has also made it possible to highlight how the temperatures increased. An increase in the extreme temperature has been measured in all stations. The warm days (TX90P) and warm nights (TN90P) show increasing trends, while the cold days (TX10P) and cold nights (TN10P) indicate decreasing trends. Again for these indices, the highest values were estimated in the stations above 1600 m asl.

In order to evaluate the general variations in the temperature, the Standardized Anomaly Index (SAI) has been calculated. The SAI series of the maximum and minimum temperatures highlights two very similar trends. The index is negative for both variables from 1961 to 1986 and positive from 1987 to 2010.

Again, the higher values for this index in the latter period were calculated for the minimum temperature. The SAI trend identified over the two elevation ranges highlights that the increase in temperature is more pronounced in the higher stations at elevations above 1600 m asl. A constant increase has been calculated from 1987 onwards, especially for the

minimum temperatures, while the maximum temperatures have shown a more steady increase since 1997. The zones below 1600 m asl have shown a less constant trend. The maximum and minimum temperatures show alternating periods of growth and decline. However, in the last period, from the end of 1990s, a steady growth has been calculated for both variables.

Although further studies are needed, considering a greater number of data from weather stations, this paper has shown that the recorded increase in temperature is greater in the high-elevation sites than in the foothill zones. High elevations seem to amplify the climatic signal.

The gathered information shows the importance of meteorological data collection networks at high altitudes, first in order to characterize the climatological features and then to understand the climate change, but also as a means of providing useful information for the climate modelling community. In this context, an accurate analysis of climatic changes in the mountains is necessary since the results could be extremely important for policy makers in order to define the best adaptation strategies necessary to protect one of the most sensitive environments, that is, the mountains.

Acknowledgments The recovery and digitization of daily data of maximum and minimum temperatures was made in the frame of the Italian MIUR Project (PRIN 2010-11): “Response of morphoclimatic system dynamics to global changes and related geomorphological hazards” (national coordinator C. Baroni) and Italian research project NextSnow (national coordinator V. Levizzani).

The authors thank Olivier Mestre for the fruitful discussion raised during the work. We gratefully acknowledge the patient work of digitization carried out by Noemi Canevarolo, Silvia Cardona, Matteo Collimedaglia and Daniela Testa. The dataset is available at Earth Sciences Department (Responsible: Simona Fratianni).

Finally, the authors thank two anonymous referees for their helpful comments and suggestions to improve deeply the paper.

References

- Acquaotta F, Fratianni S (2013) Analysis on long precipitation series in piedmont (North-West Italy). *Am J Climate Change* 02:14–24. doi:10.4236/ajcc.2013.21002
- Acquaotta F, Fratianni S, Cassardo C et al (2009) On the continuity and climatic variability of the meteorological stations in Torino, Asti, Vercelli and Oropa. *Meteorog Atmos Phys* 103:279–287. doi:10.1007/s00703-008-0333-4
- Acquaotta F, Albanese A, Fratianni S (2013a) Raccordo tra le serie termopluviometriche delle stazioni manuali ed automatiche in Piemonte. *Youcanprint*, Tricase (LE), p 149. ISBN 9788891113795
- Acquaotta F, Fratianni S, Terzago S et al (2013b) La neve sulle Alpi piemontesi: quadro conoscitivo aggiornato al cinquantennio 1961–2010. *Arpa Piemonte*, Torino, p 97. ISBN 978-88-7479-123-1
- Aguilar E, Peterson TC, Ramirez Obando P et al (2005) Changes in precipitation and temperature extremes in Central America and Northern South America, 1961–2003. *J Geophys Res* 110
- Alexander LV, Zhang X, Peterson TC et al. (2006) Global observed changes in daily climate extremes of temperature and precipitation.

- Journal of Geophysical Research 111: D05109. doi: 10.1029/2005JD006290
- ARPA Piemonte (2012) L'atlante climatologico della provincia del Verbano Cusio Ossola - Arpa Piemonte, ISBN 978- 88-7479-107-1
- Auer I, Böhm R, Jurkovic A et al (2005) A new instrumental precipitation dataset for the greater alpine region for the period 1800-2002. *Int J Climatol* 25:139–166. doi:10.1002/joc.1135
- Auer I, Böhm R, Jurkovic A et al (2007) HISTALP—historical instrumental climatological surface time series of the greater Alpine Region. *Int J Climatol* 27:17–46. doi:10.1002/joc.1377
- Barontini S, Grossi G, Kouwen N et al (2009) Impacts of climate change scenarios on runoff regimes in the southern Alps. *Hydrol Earth Syst Sci Discuss* 6:3089–3141
- Barriopedro D, García-Herrera R, Lupo AR et al (2006) A climatology of Northern Hemisphere blocking. *J Clim* 19:1042–1063
- Bartolini E, Claps P, D'Odorico P (2009) Interannual variability of winter precipitation in the European Alps: Relations with the North Atlantic Oscillation. *Hydrol Earth Syst Sci* 13:17–25
- Beniston M (2005) Warm winter spells in the Swiss Alps: Strong heat waves in a cold season? A study focusing on climate observations at the Saentis high mountain site. *Geophys Res Lett*. doi:10.1029/2004GL021478
- Beniston M, Rebetez M (1996) Regional behavior of minimum temperatures in Switzerland for the period 1979-1993. *Theor Appl Climatol* 53:231–243
- Beniston M, Diaz HF, Bradley RS (1997) Climatic change at high elevation sites: an overview clim. *Change* 36:233–251. doi:10.1023/A:1005380714349
- Biancotti A, Destefanis E, Fratianni S, Masciocco L (2005) On precipitation and hydrology of Susa Valley (Western Alps). *Geogr Fis Din Quat*, suppl 7:51–58
- Biancotti A, Carotta M, Motta L et al (1998) Le precipitazioni nevose sulle Alpi piemontesi. Trentennio 1966-1996. Regione Piemonte, Università degli Studi di Torino, Torino, pp 1–80
- Bocchiola D, Diolaiuti G (2010) Evidence of climate change within the Adamello Glacier of Italy. *Theor Appl Climatol* 100:351–369. doi:10.1007/s00704-009-0186-x
- Böhm R, Auer I, Brunetti M et al (2001) Regional temperature variability in the European Alps: 1760-1998 from homogenized instrumental time series. *Int J Climatol* 21:1779–1801. doi:10.1002/joc.689
- Bradley RS, Diaz HF, Eischeid JK et al (1987) Precipitation fluctuations over northern hemisphere land areas since the mid-19th century. *Science* 237:171–175
- Brugnara Y, Brunetti M, Maugeri M et al (2012) High-resolution analysis of daily precipitation trends in the central Alps over the last century. *Int J Climatol* 32:1406–1422. doi:10.1002/joc.2363
- Brunet M, Jones PD, Sigró J et al (2007) Temporal and spatial temperature variability and change over Spain during 1850–2005. *J Geophys Res* 112, D12117. doi:10.1029/2006JD008249
- Brunetti M, Buffoni L, Maugeri M et al (2000a) Trends of minimum and maximum daily temperature in Italy from 1865 to 1996. *Theor Appl Climatol* 66:49–60
- Brunetti M, Maugeri M, Nanni T (2000b) Variations of temperature and precipitation in Italy from 1866 to 1995. *Theor Appl Climatol* 65:165–174
- Brunetti M, Colacino M, Maugeri M et al (2001a) Trends in the daily intensity of precipitation in Italy from 1951 to 1996. *Int J Climatol* 21:299–316. doi:10.1002/joc.613
- Brunetti M, Maugeri M, Nanni T (2001b) Changes in total precipitation, rainy days and extreme events in northeastern Italy. *Int J Climatol* 21:861–871. doi:10.1002/joc.660
- Brunetti M, Maugeri M, Monti F et al (2006) Temperature and precipitation variability in Italy in the last two centuries from homogenised instrumental time series. *Int J Climatol* 26:345–381. doi:10.1002/joc.1251
- Brunetti M, Lentini G, Maugeri M et al (2009) Climate variability and change in the Greater Alpine Region over the last two centuries based on multi-variable analysis. *Int J Climatol* 29:2197–2225. doi:10.1002/joc.1857
- Cacciamani C, Deserti M, Marletto V et al (2001) Mutamenti climatici, situazione e prospettive. *Quaderno Tecnico Arpa-SMR 3. Meteo e clima - Nodi, Servizio Idro-Meteo-Clima*, p 35
- Carturan L, Filippi R, Seppi R et al (2013) Area and volume loss of the glaciers in the Ortles-Cevedale group (Eastern Italian Alps): Controls and imbalance of the remaining glaciers. *Cryosphere* 7:1339–1359
- Casty C, Wanner H, Luterbacher J et al (2005) Temperature and precipitation variability in the European Alps since 1500. *Int J Climatol* 25:1855–1880. doi:10.1002/joc.1216
- Ciccarelli N, Von Hardenberg J, Provenzale A et al (2008) Climate variability in north-western Italy during the second half of the 20th century. *Glob Planet Chang* 63:185–195. doi:10.1016/j.gloplacha.2008.03.006
- Conrad V, Pollak LV (1962) *Methods in climatology*. Harvard University Press – Climatology, p 459
- Corti S, Decesari S, Fierli F et al (2009) Clima, cambiamenti climatici globali e loro impatto sul territorio nazionale. *Quaderni dell'ISAC* 1, 978-88-903028-0-0
- Di Piazza A, Eccel E (2012) Analisi di serie giornaliere di temperatura e precipitazione in Trentino nel periodo 1958–2010. di Trento, Provincia Autonoma
- Diaz HF, Bradley RS (1997) Temperature variations during the last century at high elevation sites. *Clim Chang* 36:253–279
- Dos Santos CAC, Neale CMU, Rao TVR et al (2010) Trends in indices for extremes in daily temperature and precipitation over Utah, USA. *Int J Climatol* 31:1813–1822. doi:10.1002/joc.2205
- Dramis F, Govi M, Guglielmin M, Mortara G (1995) Mountain permafrost and slope instability in the Italian Alps. The Val Pola landslide. *Permafrost Periglacial Process* 6:73–81
- Durand Y, Giraud G, Latemser M et al (2009) Reanalysis of 47 years of climate in the French Alps (1958–2005): climatology and trends for snow cover. *J Appl Meteorol Climatol* 48:2487–2512. doi:10.1175/2009JAMC1810.1
- El Kenawy AM, Lopez-Moreno JJ, Vicente-Serrano SM, Mekhd MS (2009) Temperature trends in Libya over the second half of the 20th century. *Theor Appl Climatol* 98(1–2):1–8. doi:10.1007/s00704-008-0089-2
- Fazzini M, Gaddo M (2003) La neve in trentino: Analisi statistica del fenomeno nell'ultimo ventennio. *Neve e Valanghe, AINEVA* 47:35–43
- Fazzini M, Fratianni S, Biancotti A et al (2004) Skiability conditions in several skiing complexes on Piedmontese and Dolomitic Alps. *Meteorol Z* 13(3):253–258
- Fratianni S, Motta L (2002) L'andamento climatico in Alta Val Susa negli anni 1990-1999. Regione Piemonte, Collana Studi Climatologici in Piemonte, Torino
- Fratianni S, Cassardo C, Cremonini R (2009) Climatic characterization of foehn episodes in Piedmont, Italy. *Geogr Fis Dinam Quat* 32:15–22
- Fratianni S, Biancotti A, Cagnazzi B, Gai V (2005) Climatological study of the wind in Piedmont. *Hrvatski Meteoroloski Casopis*, Issue 40:616–619
- Fratianni S, Terzago S, Acquotta F et al (2014) How snow and its physical properties change in a changing climate alpine context? In: Lollino G, Manconi A, Clague J, Shan W, Chiarle M (eds) *Engineering geology for society and territory – vol. 1*, Chapter: 11. Springer International Publishing, pp 57–60. doi:10.1007/978-3-319-09300-0_11
- Giorgi F (2006) Climate change hot-spots. *Geophys Res Lett* 33, L08707. doi:10.1029/2006GL025734
- Giorgi F, Lionello P (2008) *Clim Chang Projections Mediterr Reg Glob Planet Chang* 63:90–104. doi:10.1016/j.gloplacha.2007.09.005
- Haeberli W (1990) Glacier and permafrost signals of 20th-century warming. *Ann Glaciol* 14:99–101
- Haeberli W (1992) Construction, environmental problems and natural hazards in periglacial mountain belts. *Permafrost Periglacial Process* 3:111–124
- Haeberli W, Beniston M (1998) Climate change and its impacts on glaciers and permafrost in the Alps. *Ambio* 27:258–265

- Haerberli W, Wegmann M, Vonder Muehll D (1997) Slope stability problems related to glacier shrinkage and permafrost degradation in the Alps. *Eclogae Geol Helv* 90:407–414
- Harris C, Davies MCR, Etzelmüller B (2001a) The assessment of potential geotechnical hazards associated with mountain permafrost in a warming global climate. *Permafrost Periglacial Process* 12:145–156
- Harris C, Haerberli W, Vonder Muehll D, King L (2001b) Permafrost monitoring in the high mountains of Europe: the PACE Project in its global context. *Permafrost Periglacial Process* 12:3–11
- Harris C, Vonder Muehll D, Isaksen K et al (2003) Warming permafrost in European mountains. *Glob Planet Chang* 39:215–225
- Hill Clarvis M, Faticchi S, Allan A et al (2013) Governing and managing water resources under changing hydro-climatic contexts: the case of the upper Rhone basin. *Environ Sci Pol* 43:56–67
- Huss M (2012) Extrapolating glacier mass balance to the mountain-range scale: the European Alps 1900–2100. *Cryosphere* 6:713–727
- IPCC (1996) Climate change 1995. In: Watson RT, Zinyowera MC, Moss RH (eds) Impacts, adaptations, and mitigation of climate change: scientific-technical analyses. Contribution of working group II to the second assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge and New York, p 880
- IPCC (2007) Climate change 2007. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, USA, p 996
- IPCC (2013) Summary for policymakers. In: climate change 2013. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, USA, p 29
- Jacobson AR, Provenzale A, von Hardenberg A et al (2004) Climate forcing and density dependence in a mountain ungulate population. *Ecology* 85(6):1598–1610
- Jones PD, Moberg A (2003) Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001. *J Clim* 16:206–223
- Jungo P, Beniston M (2001) Changes in the anomalies of extreme temperature anomalies in the 20th century at Swiss climatological stations located at different latitudes and altitudes. *Theor Appl Climatol* 69:1–12
- Kafle H, Bruins HJ (2009) Climatic trends in Israel 1970–2002: warmer and increasing aridity inland. *Clim Chang* 96:63–77
- Karl TR, Groisman PY, Knight RW et al (1993) Recent variation of snow cover and snowfall in North America and their relation to precipitation and temperature variations. *J Clim* 6:1327–1344
- Klein Tank AMG, Können GP (2003) Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99. *J Clim* 16:3665–3680
- Klein Tank AMG, Wijngaard JB, Können GP et al (2002) Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. *Int J Climatol* 22:1441–1453
- Knoche HR (2011) Ripercussioni dei cambiamenti climatici nella dorsale alpina settentrionale. *Min. sloveno dell'Ambiente e della Pianificazione del Territorio, Segretariato permanente della Convenzione delle Alpi, ARGE ALP. Segnali Alpini* 6:9–14
- Lionello P (2006a) The Mediterranean climate: an overview of the main characteristics and issues. In: Lionello P, Malanotte-Rizzoli P, Boscolo R (eds) Mediterranean climate variability. Elsevier, Amsterdam, pp 1–26
- Lionello P (2006b) Cyclones in the Mediterranean region: climatology and effects on the environment. In: Lionello P, Malanotte-Rizzoli P, Boscolo R (eds) Mediterranean climate variability. Elsevier, Amsterdam, pp 325–372
- Lionello P (2012) The Climate of the Mediterranean Region. From the Past to the Future. Elsevier, Amsterdam ISBN 9780124160422, p 502
- Liu X, Chen B (2000) Climatic warming in the Tibetan Plateau during recent decades. *Int J Climatol* 20:1729–1742
- Luterbacher J, Dietrich D, Xoplaki E et al (2004) European seasonal and annual temperature variability, trends, and extremes since 1500. *Science* 303:1499–1503. doi:10.1126/science.1093877
- Marzeion B, Nesje A (2012) Spatial patterns of North Atlantic Oscillation influence on mass balance variability of European glaciers. *Cryosphere* 6:661–673. doi:10.5194/tc-6-661-2012
- Marzeion B, Hofer M, Jarosch AH et al (2012) A minimal model for reconstructing interannual mass balance variability of glaciers in the European Alps. *Cryosphere* 6:71–84. doi:10.5194/tc-6-71-2012
- Matulla C, Auer I, Bohm R et al. (2005) Outstanding past decadal-scale climate events in the Greater Alpine Region analysed by 250 years data and model runs. GKSS-Report 2005/4.
- Maugeri M, Nanni T (1998) Surface air temperature variations in Italy: recent trends and an update to 1993. *Theor Appl Climatol* 61:191–196
- Mercalli L, Cat Berro D, Acondon V et al (2008) Cambiamenti climatici sulla montagna piemontese. Rapporto tecnico. Società meteorologica Subalpina, Regione Piemonte, Bussoleno, p 143
- Mestre O, Gruber C, Prieur C et al (2011) SPLIDHOM: A method for homogenization of daily temperature observations. *J Appl Meteorol Climatol* 50:2343–2358
- Miranda PMA, Tome AR (2009) Spatial structure of the evolution of surface temperature (1951–2004). *Clim Chang* 93:269–284. doi:10.1007/s10584-008-9540-8
- Nigrelli G, Collimedaglia M (2012) Reconstruction and analysis of two long-term precipitation time series: Alpe Devero and Domodossola (Italian Western Alps). *Theor Appl Climatol* 109(3–4):397–405. doi:10.1007/s00704-012-0586-1
- Peterson T, Easterling D, Karl T et al (1998) Homogeneity adjustment of in situ atmospheric climate data: a review. *Int J Climatol* vol 18:1493–1517
- Rebetez M, Reinhard M (2008) Monthly air temperature trends in Switzerland 1901–2000 and 1975–2004. *Theor Appl Climatol* 91:27–34
- Reichert BK, Bengtsson L, Oerlemans J (2001) Midlatitude forcing mechanisms for glacier mass balance investigated using general circulation models. *J Clim* 14:3767–3784
- Ronchi C, Loggisci N (2008) Il clima tra passato, presente e futuro. AINEVA Ed 63:11–19
- Sen PK (1968) Estimates of the regression coefficient based on Kendall's Tau. *J Am Stat Assoc* 63(324):1379–1389
- Serquet G, Marty C, Rebetez M (2013) Monthly trends and the corresponding altitudinal shift in the snowfall/precipitation day ration. *Theor Appl Climatol* 114:437–444
- Sneyers (1990) On the statistical analysis of series of observations. Geneva, WMO N 143, p 192
- Tayanç M, Im U, Dogruel M, Karaca M (2009) Climate change in Turkey for the half century. *Clim Chang* 94:483–502
- Terzago S, Cassardo C, Cremonini R, Fratianni S (2010) Snow precipitation and snow cover climatic variability for the period 1971–2009 in the SouthWestern Italian Alps: the 2008–2009 snow season case study. *Water* 2:773–787
- Terzago S, Cremonini R, Cassardo C, Fratianni S (2012) Analysis of snow precipitation during the period 2000–09 and evaluation of a snow cover algorithm in SW Italian Alps. *Geogr Fis Dinam Quat* 35(1):91–99
- Terzago S, Fratianni S, Cremonini R (2013) Winter precipitation in Western Italian Alps (1926–2010): Trends and connections with the North Atlantic/Arctic Oscillation. *Meteorol Atmos Phys* 119: 125–136. doi:10.1007/s00703-012-0231-7
- Toreti A, Desiato F (2007) Temperature trend over Italy from 1961 to 2004. *Theor Appl Climatol* 91:51–58. doi:10.1007/s00704-006-0289-6
- Toreti A, Desiato F (2008) Changes in temperature extremes over Italy in the last 44 years. *Int J Climatol* 28:733–745. doi:10.1002/joc.1576
- Toreti A, Desiato F, Fioravanti G, Perconti W (2010) Seasonal temperatures over Italy and their relationship with low frequency

- atmospheric circulation patterns. *Clim Chang* 99(1–2):211–227. doi:10.1007/s10584-009-9640-0
- Trigo RM, Pereira JMC, Pereira MG et al (2006) Atmospheric conditions associated with the exceptional fire season of 2003 in Portugal. *Int J Climatol* 26(13):1741–1757
- Ulbrich U (2006) The Mediterranean climate change under global warming. In: Lionello P, Malanotte-Rizzoli P, Boscolo R (eds) *Mediterranean climate variability*. Elsevier, Amsterdam, pp 398–415
- Valt M, Cagnati A, Crepaz A et al (2006) Neve sulle Alpi italiane. L'andamento delle precipitazioni nevose sul versante meridionale delle Alpi. *Neve e Valanghe AINEVA* 56:24–31
- Valt M, Cagnati A, Crepaz A et al (2008) Variazioni recenti del manto nevoso sul versante meridionale delle Alpi. *Neve e Valanghe AINEVA* 63:46–57
- Van der Schrier G, Efthymiadis D, Briffa KR et al (2007) European Alpine moisture variability for 1800–2003. *Int J Climatol* 27:415–427. doi:10.1002/joc.1411
- Venema VKC, Mestre O, Aguilar E et al (2012) Benchmarking homogenization algorithms for monthly data. *Clim Past* 8:89–115. doi:10.5194/cp-8-89-2012
- Xoplaki E, Gonzalez-Rouco JF, Luterbacher J, Wanner H (2003) Mediterranean summer air temperature variability and its connection to the large-scale atmospheric circulation and SSTs. *Clim Dyn* 20:723–739. doi:10.1007/s00382-003-0304-x
- Zhang X, Yang F (2004) *RClimDex (1.0) user guide*. Climate Research Branch Environment Canada, Downsview, Ontario, Canada
- Zhang X, Vincent LA, Hogg WD, Niitsoo A (2000) Temperature and precipitation trends in Canada during the 20th century. *Atmosphere-Ocean* 38:395–429
- Zhang X, Hegerl G, Zwiers FW, Kenyon J (2005) Avoiding inhomogeneity in percentile-based indices of temperature extremes. *J Climate* 18:1641–1651