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Original Article

Evolution of temperature indices in the periglacial environment of the European Alps in the period 1990-2019

NIGRELLI Guido* https://orcid.org/0000-0002-5506-5915; e-mail: guido.nigrelli@irpi.cnr.it

CHIARLE Marta https://orcid.org/0000-0001-8447-3822; e-mail: marta.chiarle@irpi.cnr.it

** Corresponding author*

National Research Council, Research Institute for Geo-hydrological Protection, Strada delle Cacce, 73 – Torino, Italy

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Abstract: Air temperature in the European Alps shows warming over recent decades at an average rate of 0.3 °C/10 years, thereby outpacing the global warming rate of 0.2 °C/10 years. The periglacial environment of the Alps is particularly important for several aspects (i.e. hydropower production, tourism, natural hazards, indicator of global warming). However, there is a lack of specific and updated studies relating to temperature change in this environment. In order to fill this gap, the recent temperature trends in the periglacial environment of the Alps were analyzed. Mean/maximum/minimum daily air temperatures recorded by 14 land-based meteorological stations were used, and the temperature indices for the period 1990-2019 were calculated. The periglacial environment of the Alps showed a warming rate of 0.4 °C/10 years, 0.6 °C/10 years and 0.8 °C/10 years for the mean/ maximum/minimum temperatures, respectively. These warming rates are higher than that observed for the entire Alpine area. In 2050 many glaciers of the Alps below 3000 m altitude are expected to be extinct, and all the areas previously occupied by glaciers will become periglacial. In order to manage and adapt to these changes, more in-depth climate analyses are needed. This is necessary for all the mountainous areas of the world, which are undergoing similar changes.

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1 Introduction

Air temperature is one of the major climatic elements and plays a decisive role in all terrestrial systems. With reference to the warming phase of the last 30 years, mountain environments seem to respond more quickly and with greater intensity to climate change than environments at lower elevations (Stahr et al. 2015). Furthermore, the rate of warming is amplified with elevation, as some authors have pointed out (Rangwala et al 2012; Pepin et al. 2015; Palazzi et al. 2019; You et al. 2020; Guo et al. 2021). Mountain surface air temperature observations in Western North America, European Alps (hereinafter Alps) and High Mountain Asia show warming over recent decades at an average rate of 0.3 °C/10 years, thereby outpacing the global warming rate 0.2 °C/10 years (Hock et al. 2019). With regard to climate and to its numerous impacts on the environment and on human activities, the Alps are one of the most investigated regions in the world. In the Alps, Auer et al. (2007) have found that the 20th century temperature increase (1.2 °C) evolved stepwise, with a first peak near 1950 and a second increase (1.3 °C/25 years) starting in the 1970s. Brunetti et al. (2009) have found that this second increase is the principal maximum of the 250-year observation period. The same authors gave a comprehensive picture of secular climate variability and change in the Greater Alpine Region (hereinafter GAR). The analyses, beside highlighting a warming that is about twice as large as the global trend, also show that the different variables have responded in different ways to this warming. Moreover, the interactions linking the different variables are often present only at specific temporal scales and only in some parts of the GAR. Beniston et al. (2018) confirmed this trend and highlighted the effects of temperatures increase on the Alpine cryosphere. Rubel et al. (2017) studied the climate of the Alps, also in terms of future scenarios (observation period 1800-2100). The years 1876–1900 are the coldest years, and the years 1976–2000 illustrate the effects of the recent warming trend. From this study, it emerges clearly the strong decline of the boreal climates, which are optimal for coniferous and mixed forests.

In the Western Italian Alps, at elevations above 2000 m a.s.l., Acquaotta et al. (2015) observed an increase of the minimum temperature of 0.6 °C/10 years over the period 1961-2010. In the same area, Nigrelli et al. (2015) observed an increase of the mean monthly temperature of (0.3-0.5) °C/10 years over the period 1955-2012.

In the Central Italian Alps, D'Agata et al. (2014) found that mean temperature increased over the period 1951-2007, but not significantly: during the 1981-2007 period, the mean temperature increased in spring, while it decreased in autumn.

In the Eastern Italian Alps, Tudoroiu et al. (2016) found that warming in the period 1975-2010 occurred both at high and low elevations, but it was less pronounced at high elevations: this elevation-dependent trend was consistent for mean, maximum and minimum air temperature. In the South Tyrol, a specific sector of the Eastern Italian Alps, Schlögel et al. (2020) found a clear evidence of an increase in spring mean and maximum air temperatures since 2014.

In the Swiss Alps, Ceppi et al. (2012) found that the seasonal temperature trends are all positive and mostly significant with an annual average warming rate of 0.35 °C/10 years, ranging from 0.17 °C/10 years in autumn to 0.48 °C/10 years in summer (observation period: 1959-2008). Again, in the Swiss Alps, Rottler et al. (2018) found that warming was strongest during spring and early summer, with enhanced warming of daytime maximum temperatures (observation period 1981-2017): elevation-based differences in temperature trends occur during autumn and winter, with stronger warming at lower elevations.

In Austria, a comprehensive analysis was performed on a homogenized daily dataset (Nemec et al. 2013), showing a widespread warming trend in both daily minimum and maximum air temperatures. The warming trends are in general amplified due to the homogenization.

Based on the studies mentioned above, the signals that surface air temperature over the Alps is rising are unequivocal. However, there is a marked spatio-temporal variability of the warming trends, due to the different time periods, time series and variables that have been considered by the various authors. In particular, we found a lack of specific and updated studies relating to the periglacial environment.

Periglacial environments are characterized by intense frost and are restricted to areas that experience cold, but essentially non-glacial climates (French 2018). The periglacial environments include the polar deserts and polar semi-deserts of the High Arctic, the extensive tundra zones of the high northern latitudes, the northern parts of the boreal forests of North America and Eurasia and the alpine zones that lie above timberline and below snow line in mid- and low-latitude mountains (Heckmann et al. 2019; Murton 2021). The mid-latitude alpine periglacial environments are spatially less extensive than those of high latitude (French 2018). In the Alps, the periglacial environment can be defined as the zone between the timberline and the snow line: the climate is dominated by both diurnal and seasonal temperature effects and by high solar radiation. In the Alps there is growing evidence that periglacial environments are particularly sensitive to global warming (French 2018).

The periglacial environment of the Alps is important for several reasons. First of all, many hydropower plants are located in periglacial areas (Fig. 1) and use water from rainfalls, from glacier and from snow melt. In the Alps the estimated total glacier area is 2,000 km² (Zemp et al. 2020). Moreover, the periglacial environment is experiencing an increase of natural hazards, in particularly due to cryosphere changes occurring as a consequence of air temperature increase (Ballantyne 2002; Fischer et al.

2012; Allen et al. 2013; Philips et al. 2016; Ravanel et al. 2017; Chiarle et al. 2021). For example, during the last 20 years, a growing number of rockfalls has been observed and documented (Paranunzio et al. 2019): many of these rockfalls occurred in periglacial areas. Finally, tourism is one of the main economic resources in the Alps. It depends heavily on natural attractions which can be heavily affected by climate change (Paunović et al. 2019). In this context, the periglacial environment offers unique attractive landscapes. However, hikers, mountaineering infrastructures and mountain paths are increasingly subject to natural hazards, caused by permafrost degradation (Mourey et al. 2019). Increases in permafrost temperature over the last 10-30 years of up to 0.3 °C per decade have been documented at depths of about 20 m in the Alps (IPCC 2021).

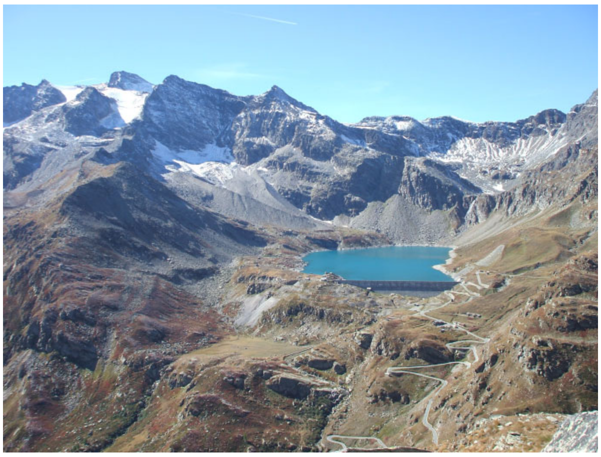

Fig. 1 An example of human-modified glacial/ periglacial environment in the European Alps (Ceresole Reale, Italy). Dams and artificial lakes, streams, high-paved roads, high-altitude grasslands, terminal and lateral moraines of the Little Ice Age, debris slopes and debris-cones, rockfalls, glaciers and mountain peaks, are the main features of this landscape (Photo was taken by G. Nigrelli, 3 October 2018). For a panoramic view of this site visit https://ceresolereale.panomax.com/.

Considering the importance of the periglacial environments of the Alps, the lack of specific and updated studies on recent temperature trends is an important limitation to the knowledge of the environmental changes in progress, fundamental for the development of effective actions to deal with the impacts of climate change. Our study aims thus to fill this gap for the European Alps and to stimulate the realization of similar studies in the mountainous areas of the world that are undergoing similar transformations.

2 Data and Methods

In this study, data recorded by fourteen land-based meteorological stations (hereinafter stations) located in the periglacial environment of the Alps were analyzed. Extreme temperature indices using daily maximum (TX) and minimum (TN) air temperatures were calculated. In addition, other temperature indices using daily mean (TG) air temperature were calculated. The investigated period spans from 1990 to 2019.

2.1 Choice of the stations

Forty-two stations were initially selected. Data from several online repositories were used (ARPA Piemonte 2020; CF Valle d'Aosta 2020; ARPA Lombardia 2020; PA di Bolzano 2020; Meteotrentino 2020; ARPA Veneto 2020; ARPA Friuli Venezia Giulia 2020; MeteoFrance 2020; Meteoswiss 2020; ZAMG 2020). In order to increase the number of the stations and to extend the investigated area, some global temperature datasets were used (ECA&D: Klein Tank et al. 2002; HISTALP: Auer et al. 2007; CRUTEM4: Osborn et al. 2014; NOAA Global Temp: Zhang et al. 2020).

2.2 Data quality control

A quality control (QC) on TX and TN series was carried out. With regard to data from the online repositories, a first validation of the raw data is carried out by the owners before their publication. However, the owners use both different types of sensors for data acquisition and different validation methods. Therefore, we decided to perform an additional, rigorous QC on all datasets, in order to further check their quality and select the best ones. For this purpose, we adopted the QC technique recommended by WMO, which is described in detail in the Guide to Climatological Practices (WMO 2018). This technique 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. During the QC we found that: i) Some stations have an observation period that starts after 1990 or ends before 2019; ii) Many stations have a large number of years/months with no data; iii) Some stations are placed in sites with very specific (topo-)climate settings (valley floors, mountain ridges, urban areas), and therefore are not suitable for the purposes of this study (Barry et al. 2016); iv) Some datasets show abrupt shifts; v) The daily mean temperatures provided by the owners are calculated using different methods (using a different number of hourly observations) and therefore are not comparable each other. In order to obtain mean temperatures comparable each other's, TG have been calculated using the following formula: TG = (TX+TN)/2.

In the end, only ten out of forty-two stations passed the QC required to be considered in this study (Table 1, stations from No. 1 to No. 10).

With regard to the global temperature datasets accessed, more than twenty stations were initially selected. These datasets can be considered reliable, since they have already passed a QC. However, looking at these datasets we found that: i) For some stations the observation period ends before 2019; ii) Some stations are located in places with unfavorable local (topo-)climate settings, as reported above; iii) For stations located in alpine periglacial areas, only monthly mean air temperature datasets are available. All this considered, we decided to use only four HISTALP stations (Table 1, stations from No. 11 to No. 14) and to use CRUTEM4 data for the monthly mean air temperature dataset of station No. 10. At the end of this step, we can say that the fourteen stations selected for this study are the best compromise among data availability, quality of the datasets, and geographic distribution (Fig. 2). The related datasets can, thus, be considered the most representative of the temperature variability in the periglacial environment of the Alps from 1990 to 2019.

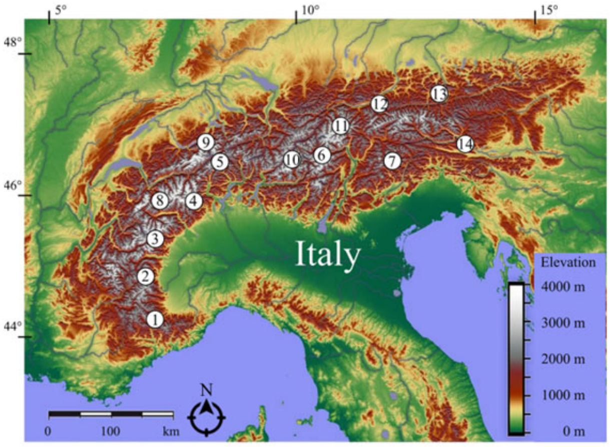

Fig. 2 Geographical distribution of the meteorological stations used in this study (basemap source: the Alpine Arc, Wikypedia, modified). For station numbers see Table 1.

2.3 Annual/seasonal/monthly datasets

Annual/seasonal/monthly extreme temperature indices have been calculated using TX and TN datasets, for the stations from No. 1 to No. 10. We have used the extreme temperature indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) for the assessment of climate change, which are listed in Table 2. The complete list of the ETCCDI extreme indices can be found at http://etccdi.pacificclimate.org/list_27_indices.shtml. As regards the TX10p, TN10p, TX90p, TN90p indices, we preferred to express them in terms of number of days rather than as a percentage, in order to know the real value of these parameters. Finally, in compliance with the recommendations of the WMO

Table 1 Main characteristics of the meteorological stations used in this study (Md, missing data). For the geographical distribution of the meteorological stations see Fig. 2.

Stat. (No.)	Station name, Country (GAR subregion)	Latitude (N)	Longitude (E)	Elev. (m)	Period (Years)	Md (%)	Data source
1	Colle Lombarda, IT (SW)	44°12'26"	7°8'51"	2305	1990-2019	2.4	ARPA Piemonte (2020)
2	Colle Barant, IT (SW)	44°46'27"	7°3'38"	2294	1990-2019	3.7	ARPA Piemonte (2020)
3	Rifugio Gastaldi, IT (SW)	45°17'53"	7°8'33"	2659	1990-2019	2.2	ARPA Piemonte (2020)
4	Bocchetta delle Pisse, IT (SW)	45°52'33"	7°54'4"	2410	1990-2019	0.3	ARPA Piemonte (2020)
5	Formazza, IT (SW)	46°26'0"	8°21'29"	2453	1990-2019	5.3	ARPA Piemonte (2020)
6	Diga del Careser, IT (SW)	46°25'25"	10°41'50"	2600	1990-2019	14.3	Meteotrentino (2020)
7	Pian Fedaia, IT (SW)	46°27'32"	11°51'46"	2063	1990-2019	6.3	Meteotrentino (2020)
8	Col du G. St-Bernard, CH (NW)	45°52'8"	7°10'14"	2472	1990-2019	0.0	Meteoswiss (2020)
9	Grimsel Hospiz, CH (NW)	46°34'18"	8°19'59"	1980	1990-2019	0.0	Meteoswiss (2020)
10	Passo del Bernina, CH (SW)	46°24'32"	10°1'10"	2260	1990-2019	3.6	Meteoswiss (2020)
11	Obergurgl-Vent, AT (NW)	46°52'3"	11°1'37"	1938	1990-2019	0.0	HISTALP (2020)
12	Patscherkofel, AT (NW)	47°12'34"	11°27'42"	2247	1990-2019	0.0	HISTALP (2020)
13	Schmittenhohe, AT (NE)	47°19'48"	12°44'13"	1973	1990-2019	0.0	HISTALP (2020)
14	Villacher Alpe, AT (SE)	46°36'14"	13°40'22"	2160	1990-2019	0.0	HISTALP (2020)

(2018), the annual/seasonal/monthly time series of the extreme temperature indices were checked and some small gaps were eliminated.

Table 2 Extreme temperature indices selected for this study, calculated on the annual/seasonal/monthly temporal scales (a/s/m).

ID	Indicator definitions	Units
TXx	a/s/m maximum value of daily maximum temperature	°C
TNx	a/s/m maximum value of daily minimum temperature	°C
TXn	a/s/m minimum value of daily maximum temperature	°C
TNn	a/s/m minimum value of daily minimum temperature	°C
TX10p	a/s/m cool day-times, count of days when TX <10th percentile	Days
TN10p	a/s/m cool nights, count of days when TN <10th percentile	Days
TX90p	a/s/m warm day-times, count of days when TX >90th percentile	Days
TN90p	a/s/m warm nights, count of days when TN >90th percentile	Days
FD	a/s/m frost days, count of days where TN <0 °C	Days
ID	a/s/m icing days, count of days where TX <0 °C	Days

2.4 Trend analysis

In order to identify significant trends in extreme temperature indices, the Mann-Kendall trend test and the Sen's slope estimator methods were used. The Mann-Kendall test is a popular nonparametric alternative for testing for the presence of a trend, or nonstationarity of the central tendency, of a time series (Wilks 2011). 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 magnitude of the slope is obtained from Sen's nonparametric estimator of the slope (Sen 1968). Sen's method is not greatly affected by gross data errors or outliers, and it can be computed when data are missing. Sen's estimator is closely related to the Mann-Kendall test (Gilbert 1987). The Mann-Kendall test and the Sen's slope estimator are widely used to quantify the significance of trends in hydro-meteorological time series (Gocic et al. 2013). Annual and seasonal temperature indices and annual mean temperature trends for the whole periglacial environment of the Alps, using TG datasets of all fourteen stations have been calculated. In order to make this work concise, we only reported the results of the annual and seasonal trends.

2.5 30-year Standard Normals

HISTALP and CRUTEM4 data were used to calculate three 30-years Standard Normals periods (1961-1990, 1971-2000, 1981-2010) and one non-standard period that corresponds to our study period (1990-2019), for stations with long observation periods (stations No. 8, 11, 12 and 14). According to WMO (2017), in some contexts it is possible to use periods other than those for the climatological standard normal or reference normal: for example, in case of stations that do not have a long period of observation, or stations presenting the first 30 years of observations.

3 Results

3.1 TXx, TNx extreme temperature indices

The mean values of TXx and TNx for the 1990-2019 period are respectively 20.2 °C (±1.1 °C; n = 30) and 11.5 °C (±1.2 °C; n = 30). The first five stations show positive trends for TXx index, with high confidence levels mostly in summer, in autumn, and on an annual scale (Table 3). The highest values are observed in autumn, at stations No. 1 and No. 5, with 1.5 °C/10 years and 1.4 °C/10 years, respectively. These results are similar to those obtained by other authors (Acquaotta et al. 2015; Nigrelli et al. 2015). On the contrary, stations from No. 6 to No. 10 show no trends for TXx. The analysis of TNx index provides a different picture: 9 out of 10 stations show positive trends, and the highest values are observed in summer, at station No. 6, and in autumn, at stations No. 2 and No. 7 (1.0 °C/10 years).

On an annual scale, the maximum values of the maximum temperatures (TXx) are rising mainly in the western part of the periglacial environment, while maximum values of the minimum temperatures (TNx) are rising mainly in the eastern part. This important aspect of climate warming is not highlighted by the analysis of TG. TXx and TNx annual trends observed in the whole periglacial environment of the Alps during period 1990-2019 are shown in Fig. 3. The annual trends are positive and significant with a warming rate of 0.6 °C/10 years and 0.8 °C/10 years for TXx and TNx, respectively.

Table 3 Trends for annual/seasonal TXx and TNx time series (for station No. see Table 1). The significance level is 0.001 (***), 0.01 (**), 0.05 (*) and the magnitude of the slope is in °C/10 years. Empty cells indicate absence of statistically significant trends (nd, not detected due to missing data). Winter: DJF; spring: MAM; summer: JJA; autumn: SON; year: Y.

No.	TXx					TNx				
	DJF	MAM	JJA	SON	Y	DJF	MAM	JJA	SON	Y
1	0.9*	1.0*	1.1***	1.5***	1.1***				0.7*	
2			0.8*	1.1**	0.9**				1.0*	
3		0.5*	1.2***	0.9*	1.2***			0.7*	0.8*	0.8*
4	*1.1	1.3**	1.1**	0.9*	1.1***				0.8*	
5		1.2***	0.9*	1.4***	0.9*			0.6*	0.6*	0.6*
6								1.0*		0.9*
7								0.8*	1.0**	0.8*
8								0.8*		0.8*
9						0.6*		0.9**		0.9**
10		nd					nd			

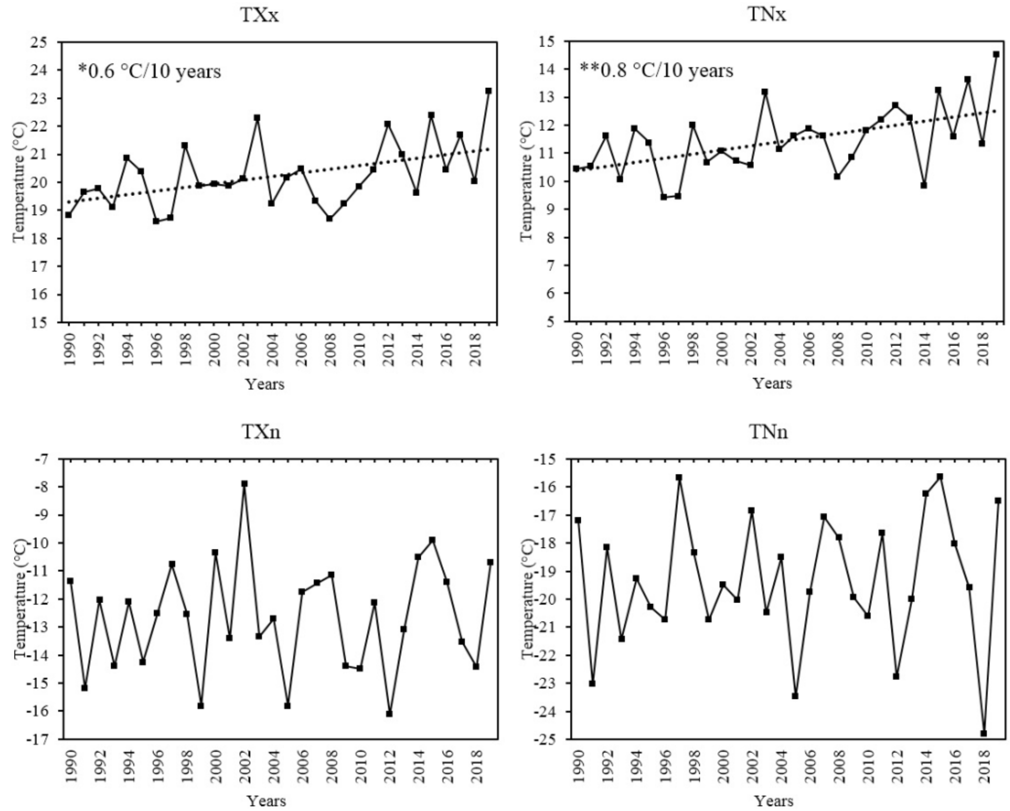

Fig. 3 TXx, TNx, TXn and TNn annual trends observed in the whole periglacial environment of the Alps for the period 1990-2019 (mean values of the 10 stations used). TXx and TNx time series showed a statistically significant trend, respectively with 0.05 (*) and 0.01 (**) level. The magnitude of the slopes (°C/10 years) is also reported.

3.2 TXn, TNn extreme temperature indices

The mean values of TXn and TNn for the 1990-2019 period are -12.7 °C (±1.9 °C; n = 30) and -19.3 °C (±2.3 °C; n = 30), respectively. A clear signal of both TXn and TNn indices increase during summer was found (Table 4). This increase looks relatively homogeneous through the whole study area. For TXn, the highest values are observed in summer, at stations No. 4 and No. 10, with 1.5 °C/10 years for both stations. For TNn, the highest value is observed in summer, at station No. 3, with an increase of 1.6 °C/10 years. Some stations show positive trends for these indices also in spring (stations No. 6 and 7) and autumn (station No. 7). TXn and TNn annual trends for the whole periglacial environment of the Alps are shown in Fig. 3. No annual statistically significant trend was found, but a marked interannual variability.

3.3 TX10p, TN10p, TX90p, TN90p extreme temperature indices

As a consequence of the temperature increase, warm day-times (TX90p) and warm nights (TN90p) increased too (Table 5). On the contrary, cool day-times (TX10p) and cool nights (TN10p) do not show statistically significant trends. TX90p increase is statistically significant with high confidence levels, for 5 stations (No. 1, 2, 3, 4 and 5). Station No. 5 shows the highest value, with an increase of 17 days/10 years. TN90p increase is statistically significant for 7 stations (No. 2, 3, 4, 6, 7, 8 and 9). For this index, the highest value is observed at station No. 7, with an increase of 13 days/10 years. A different behavior emerges between the southwest GAR subregion, and the northwest and eastern GAR subregions: in the southwest GAR subregion, both warm day-times and warm nights increased significantly; in the northwest and eastern GAR subregions, the increase mainly refers to warm nights.

3.4 Frost days (FD) and icing days (ID) extreme temperature indices

As with TXx and TXn, the FD index shows significant trends mainly in summer, autumn and on an annual scale (Table 6). For the ID index, the picture that emerges is less clear. For FD, the highest value is observed at station No. 7, with a decrease of 13 days/10 years. For ID, significant trends are found mainly in spring and on an annual scale: the highest value is observed at station No. 5 with a decrease of 16 days/10 years. Again, the southwest GAR subregion exhibits a different behavior than the other subregions, since the decrease of ID is observed only in this part of the study area.

3.5 Mean temperature indices

The mean annual air temperature for the 1990-2019 period is 1.7 °C (±0.6 °C; n = 30). This mean temperature is in accordance with the empirical definition of periglacial conditions adopted by French (2018) that is: "Periglacial conditions exist wherever the mean annual air

Table 4 Trends for annual/seasonal TXn and TNn time series (for station No. see Table 1).

No.	TXn					TNn				
	DJF	MAM	JJA	SON	Y	DJF	MAM	JJA	SON	Y
1			1.3*					1.1**		
2			1.2*					1.1***		
3			1.2***					1.6***		
4			1.5***					1.1***		
5			1.3***					1.0**		
6		1.5*	1.3*					1.2**		
7		1.0*	1.2***					1.2***	1.3*	
8			1.1*					0.8*		
9			1.1*					0.8**		
10		nd	1.5**				nd			

Notes: The significance level is 0.001 (***), 0.01 (**), 0.05 (*) and the magnitude of the slope is in °C/10 years. Empty cells indicate absence of statistically significant trends (nd, not detected due to missing data). Winter: DJF; spring: MAM; summer: JJA; autumn: SON; year: Y.

Table 5 Trends for annual TX10p, TN10p, TX90p and TN90p time series (for station No. see Table 1).

No.	TX10p	TN10p	TX90p	TN90p
1			15***	
2			8**	8**
3			14***	8**
4			15***	8**
5			17***	
6				11***
7				13***
8			6*	5*
9				7**
10				

Notes: Significance levels and the explanation on the empty cells, see Table 4.

Table 6 Trends (number of days/10 years at 0.05 significance level) for annual/seasonal frost days (FD) and icing days (ID) time series (for station No. see Table 1).

No.	FD					ID				
	DJF	MAM	JJA	SON	Y	DJF	MAM	JJA	SON	Y
1			-2	-4	-6					-6
2			-2	-5	-7					
3			-4	-5	-12		-3			-6
4			-3	-6	-11		-4			-8
5			-4	-4	-9		-7		-4	-16
6			-5	-5	-11					
7			-3	-7	-13					
8			-3	-5	-9					
9	-1		-2		-8					
10		nd					nd			

Notes: Abbreviations and the explanation on the empty cells, see Table 4.

temperature is less than +3 °C". Thirteen stations show positive trends, often with a high confidence level, mostly in summer, in autumn and on an annual scale (Table 7): no significant trend was detected in winter. The highest values are observed in summer at stations No. 1, 3 and 4, with an increase of 0.8 °C/10 years, in autumn at stations No. 1, 3, 4, 5 and 13, with 0.7 °C/10 years, and on an annual scale at stations No. 4 and 5, with 0.6 °C/10 years.

Mean temperatures (TG) are rising in spring, summer, autumn and annually in the whole studied area. Annual mean temperature trends observed in the whole periglacial environment of the Alps are shown in Fig. 4. The periglacial environment of the Alps is warming at a rate of 0.4 °C/10 years. In these conditions, frost-related processes occur, but do not necessarily dominate (French 2018).

Table 7 Annual/seasonal trends of the fourteen stations used in this study, calculated using the monthly mean temperature (for station No. see Table 1).

No.	DJF	MAM	JJA	SON	Y
1			0.8***	0.7***	0.5***
2			0.7**	0.6**	0.4**
3		0.5*	0.8***	0.7**	0.5***
4		0.7*	0.8**	0.7**	0.6***
5		0.7**	0.6***	0.7**	0.6***
6		0.6*	0.7**	0.6*	0.4**
7			0.7**	0.6*	0.3*
8			0.5**	0.5*	0.3**
9					0.3*
10					
11			0.6**	0.4*	0.3*
12		0.5*	0.6**		0.3*
13		0.5*	0.6**	0.7*	0.4*
14		0.4*	0.7**		0.4**

Notes: The significance level is 0.001 (***), 0.01 (**), 0.05 (*) and the magnitude of the slope (°C/10 years). Empty cells indicate absence of statistically significant trends (nd, not detected due to missing data). Winter: DJF; spring: MAM; summer: JJA; autumn: SON; year: Y.

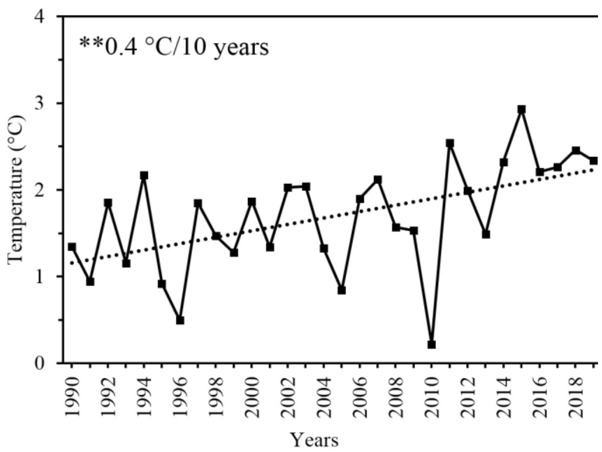

Fig. 4 Annual mean temperature trend observed in the whole periglacial environment of the Alps for the period 1990-2019 (mean values of the 14 stations used). Time series show a statistically significant trend with 0.01 (**) level. The magnitude of the slopes (°C/10 years) are also reported.

4 Discussion

The analyses carried out in this work show a clear trend of increase for all the considered indices (TXx, TNx, TXn, TNn, TX90p, TN90p, TG), with the only exception of the number of frost and icing days (FD, ID), which are decreasing. These results are in agreement with the outcomes of existing literature.

Data resulting from our analyses offer some interesting points of comparison with studies carried out in specific alpine sectors, on the GAR, and on a global scale. For example, similar trends in some French stations with shorter time series, and for this reason not included in this study, were also observed. TXx and TNx trends for Mont Cenis station (lat. 45°16'09"N; long. 6°53'57"E; elev. 2032 m a.s.l.; observation period 1993-2019; southwest GAR subregion; source Meteo France) were found: TXx 0.9 °C/10 years in summer, 1.6 °C/10 years in autumn, 0.9 °C/10 years for annual series; TNx no trends statistically significant; TXn and TNn indices shows TXn 1.3 °C/10 years in summer and 1.1 °C/10 years in summer, respectively. Furthermore, the annual trends of the mean temperature related to the Swiss stations No. 8 (0.3 °C/10 years) and No. 9 (0.3 °C/10 years) are similar to those found in the Swiss Alps by Ceppi et al. (2012), 0.35 °C/10 years, observation period 1959-2008, and by Ohmura (2012), 0.4 °C/10 years, observation period 1970-2011. For station No. 10, a particular situation has been found. In fact, this station is localized in the southwest GAR subregion, and only significant trends regarding the minimum values of maximum temperature (TXn) were found, in summer, 1.5 °C/10 years. This is probably due to the fact that this station is located close to an artificial lake, at a distance of about 100 m from the lakeshore. This lake has a considerable size (an area of 1.4 km^2 and a perimeter of about 6.9 km). The presence of this lake mitigates thermal extremes during the warmer and colder months. This station passed raw data validation and our QC; however, metadata mention precipitation anomalies ("Precipitation measurement at an exposed site, influences due to wind and snow drifts possible") but no information is provided on possible temperature anomalies. Furthermore, site analysis from satellite images did not reveal any particular problem related to the station site. The annual trends related to the stations No. 11 (0.3 °C/10 years), No. 12 (0.3 °C/10 years), No. 13 (0.4 °C/10 years) and No. 14 (0.4 °C/10 years) are slightly higher than those found by Ohmura (2012) in the Austrian Alps (about 0.27 °C/10 years, observation period 1970-2011), confirming the increase of the warming rate in recent decades, as also observed by other authors (Ceppi et al. 2012; Auer et al. 2007; Hock et al. 2019). On this regard, Fig. 5 highlights the increase of the warming rate as a function of time, for the 1971-2000, 1981-2010 and 1990-2019. The warming rate between the 1961-1990 Standard Normals and the 1990-2019 period are 0.69 °C (station No. 8); 1.05 °C (station No. 11); 1.15 °C (station No. 12) and 1.10 °C (station No. 14). It was not possible to make this comparison for the other stations, due to their short observation period.

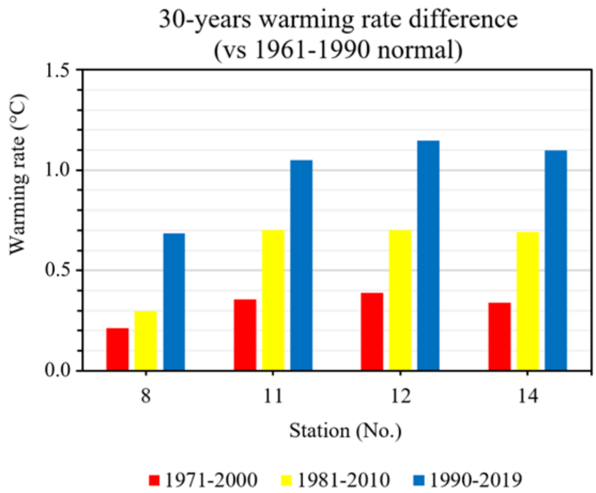

Fig. 5 Comparison between 1961-1990 standard normal period and other 30-year standard periods (1971-2000; 1981-2010; 1990-2019). In this comparison we also include the non-standard period 1990-2019. For station numbers see Table 1.

Global warming rate over recent decades is 0.2 °C/10 years, with a rate of 0.3 °C/10 years observed in the Alps (Hock et al. 2019). According to our results, the periglacial environment of the Alps shows, on a whole, a warming rate of 0.4 °C/10 years, and it is even more pronounced for other indices such as TXx and TNx that exhibit rates of 0.6 °C/10 years and 0.8 °C/10 years, respectively. These data confirm that the periglacial environment is particularly sensitive to global warming, as reported by French (2018). In fact, if we consider the TXx and TNx indices, the warming rates that we observed are about two times the warming rate found in the Alps by Hock et al. (2019).

According to the Alpine Permafrost Index Map (Boeckli et al. 2012) updated to 2018, the stations No. 1, 2, 4, 5, 7, 9, 10, 11, 12, 13 and 14 are in areas under "No permafrost conditions", while stations No. 3, 6 and 8 are in areas under "Permafrost only in very favorable conditions". Even if the stations analyzed here are not located in areas of continuous permafrost, temperature trends identified by this study can provide valuable hints on scenarios for permafrost areas, which are particularly sensitive to even small temperature increases. Permafrost degradation due to the progressive increase of air temperature can, in fact, predispose rock slopes and debris accumulations (e.g. moraines or talus) to instability, because ground ice melting decreases the strength of those materials (Ravanel et al. 2017; Paranunzio et al. 2019). At the same time, seasonal freeze-thaw cycles occur at higher altitudes and cause thermal stress on rock masses which can become unstable and collapse (Viani et al. 2020).

This study highlights that the warming rate observed in the periglacial environment is higher than the warming rate observed considering the entire Alpine area. In the periglacial environment the albedo (i.e. the fraction of incident solar radiation that is reflected by the land surface) is high only when the land surface is covered by snow, while it is low during the rest of the year. This may explain why no significant temperature trend was observed in winter. In the periglacial environment, frost days and icing days are decreasing: consequently, the snow cover decreases in extent and duration, albedo reduces and the increasing absorption of solar radiation by the ground increases near-surface air temperature. Albedo changes are mentioned as one of the most important drivers of the elevation-dependent warming by Palazzi et al. (2019).

Evapotranspiration (i.e. the sum of evaporation and plant transpiration from the Earth's surface to the atmosphere) contributes to lowering the temperature of the air and its rate increases with the (increasing) amount of biomass. The typical biome of the periglacial environment is the tundra. The alpine tundra is dominated by high-altitude grasslands, dwarf shrubs, mosses, and lichens. In this biome, the evapotranspiration rate is lower than in coniferous forests of lower altitudes. Therefore, in the periglacial environment the mitigation effect of evapotranspiration on temperature increase is low.

The main effects of temperature increase on the periglacial environment of the Alps are: shift towards warmer thermal regimes; shift in seasonal snowmelt and streamflow; upward shift of the "ET alpine tundra" Köppen-Geiger climate zone; of the 0 °C isotherm; of the snowline; of the treeline, and of the mountain flora and fauna. For the whole alpine environment, these shifts are reported in detail in Broll et al. (2005), Auer et al. (2007), Barry (2008), Wiegandt (2008), Barry et al. (2016), Rubel et al. (2017), Beniston et al. (2018), French (2018), Hock et al. (2019).

Due to these shifts, the periglacial environment of the Alps is evolving in two different ways, depending on the time scale considered. On short time scales (a few decades), we observe an expansion of periglacial areas towards higher altitudes (e.g. the areas affected by the glaciers retreat). On long time scales (a few hundred years), we can say that there will be a shift towards the higher altitudes of the whole altitude belt occupied by this environment. In fact, in this study, we observed that, according to the Köppen-Geiger climatic classification, data of four stations (No. 4, 6, 8 and 12) showed a shift from a "Polar, E" climate to a "Cold, D" climate. Other studies confirm this trend: for example, the mean altitude of the potential timber line in the GAR was calculated to be 1730 m a.s.l. at the end of the 19th century, 1880 m a.s.l. at the end of the 20th century and is foreseen to extend between 2120 m a.s.l. and 2820 m a.s.l. at the end of the 21st century (Rubel et al. 2017).

The impacts of temperature increase on the periglacial environment of the Alps are many and manifold and concern both the natural environment and human activities. The impacts on natural environment mainly include permafrost degradation, decrease in the extent and duration of the snowpack, depletion of high-altitude mountain ecosystems and colonization by non-native species. The impacts on human activities include a reduced water availability, in particular during the summer season (JJA), greater difficulty for pastoralism (which must move to ever greater altitudes), a growing risk for summer recreational activities, due to the growing number of slope instability and to rapid environmental changes, which require, for example, to modify climbing routes or hiking paths (Mourey et al., 2019), growing difficulties for winter tourism (e.g. snowpack reduction). For the alpine environment as a whole, these impacts are illustrated in detail in Rubel et al. (2017), PSAC (2017), Beniston et al. (2018), PSAC (2019), Hock et al. (2019). Impacts on the natural environment and on human activities are interrelated and the changes that occur on the one hand affect the other one: for example, permafrost degradation decreases the integrity of infrastructures.

5 Conclusions

This study analyzed the recent air temperature trends of the periglacial environment of the Alps. Temperatures are rising and their warming rate too. The current warming rate is significantly modifying this environment and all environments of the Alps. If the warming rates remain constant, it will be difficult to mitigate the effects of climate change over the next few decades. The annual mean global temperature is likely to be at least 1 °C above pre-industrial levels (1850-1900) in each of the coming five years (2020-2024) and there is a 20% chance that it will exceed 1.5 °C in at least one year, according to new climate predictions issued by the World Meteorological Organization (2020). The studies we have been carrying out for years on the high-altitude alpine environment lead us to affirm that many glaciers below 3000 m a.s.l. will be extinct and snow cover will be reduced below elevations of 1500–2000 m a.s.l. throughout the 21st century (IPCC 2021). All the area previously occupied by glaciers will become periglacial. This means that there will be more and more areas where the albedo effect will be reduced and the temperatures will rise faster and faster. In order to anticipate and manage these changes, more in-depth climate analyses are needed.

To our best knowledge, the present study is the first one to apply extreme temperature indices specifically to the periglacial environment of the Alps. However, the approach applied in this study is intended for a preliminary investigation. In order to obtain more reliable scenarios, it is necessary to explore new methods of investigation. For example, this environment might be investigated using data GRID, as some authors on a national or GAR scale have already done (Ceppi et al. 2012; Chimani et al. 2013). Furthermore, our approach could be applied to the other alpine environments, or to other mountainous regions of the globe, with specific reference to the different climatic zones, in order to obtain a thorough understanding of the space-time evolution of the climate in mountainous areas.

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