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RECENT TRENDS OF TEMPERATURE AND PRECIPITATION IN ALPINE AND SUBALPINE AREAS IN NORTH WESTERN ITALY

ABSTRACT: ROGORA M., ARISCI S. & MOSELLO R., *Recent trends of temperature and precipitation in alpine and subalpine areas in North Western Italy*. (IT ISSN 1724-4757, 2004).

Eleven stations located at different altitudes in the Italian part of the Lake Maggiore watershed (North-Western Italy) were selected to highlight trends in temperature and precipitation. The data available cover a period of about 30 years for six of the stations and 60-70 years for five sites. Data (maximum and minimum temperatures, precipitation amount, snow cover) were collected on a daily basis, and monthly, annual and seasonal values calculated. The results clearly showed increasing trends of temperature at most sites, with different significance for minimum and maximum temperatures and for the different seasons. Examination of the longest data series suggests that it is mainly in the last 30 years that this tendency towards warming has emerged. No significant trend emerged for precipitation amount, apart from a decrease recorded at one site. The analysis of data on a daily basis at four stations showed that precipitation volume has been quite constant in the last 70 years, while the number of rainy days per year has been decreasing, a particularly striking trend over the last 25-30 years. These results lead to the hypothesis that there has been an increasing occurrence of stormy precipitation events in the last decades.

KEY WORDS: Climate change, Temperature, Precipitation, North-Western Italy.

RIASSUNTO: ROGORA M., ARISCI S. & MOSELLO R., *Variazioni recenti di temperatura e precipitazioni nell'area alpina e subalpina dell'Italia Nord-Occidentale*. (IT ISSN 1724-4757, 2004).

Undici stazioni meteorologiche, collocate a quote differenti nella parte italiana del bacino imbrifero del Lago Maggiore (Italia Nord-Occidentale) sono state selezionate allo scopo di analizzare le variazioni a lungo termine di temperature e precipitazioni. I dati utilizzati coprono un periodo di circa 30 anni per sei stazioni e di 60-70 anni per 5 stazioni. Dai dati di temperatura minima e massima, quantità di precipitazione, altezza della neve al suolo, raccolti con frequenza giornaliera, si sono calcolati i valori medi mensili, stagionali e annuali. I risultati dell'analisi dei trend mostrano un aumento delle temperature nella maggior parte dei siti considerati, con diverso livello di significatività per le temperature massime e minime e nelle diverse stagioni. L'analisi delle serie lunghe di dati (dal 1930-1940) evidenzia come la tendenza al riscaldamento abbia interessato in particolar modo gli ultimi 30 anni. I volumi di precipitazione non mostrano alcun trend significativo, ad eccezione di una diminuzione dei valori in una delle stazioni. L'analisi dei dati raccolti su basa giornaliera nell'arco di 70 anni mostra invece una tendenza alla diminuzione nel numero di giorni di pioggia per anno, particolarmente accentuata negli ultimi 25-30 anni. Questo risultato porta ad ipotizzare un aumento nella frequenza degli eventi intensi di precipitazione negli ultimi decenni.

TERMINI CHIAVE: Cambiamenti climatici, Temperature, precipitazioni, Italia Nord-Occidentale.

INTRODUCTION

The estimates provided by the Intergovernmental Panel on Climate Change (IPCC) relating to climate warming in the 20^{th} century showed an increase in the global average surface temperature of 0.6 ± 0.2 °C (IPCC, 1996; 2001). This trend has been particularly striking in the last 25-30 years, but differs in magnitude in different parts of the globe. This temperature increase has probably been the greatest in any century during the past 1,000 years; furthermore, the 90s were the warmest decade ever recorded in the Northern Hemisphere. The warming mainly affected night-time temperatures over land, which increased by 0.2 °C per decade, about twice the rate of the increase in day-time temperatures (0.1 °C per decade) (IPCC, 2001).

Precipitation showed a tendency to increase (0.5-1% per decade) over most middle and high latitudes of the Northern Hemisphere, where it is likely that there has been a 2-4% increase in the frequency of heavy precipitation events (IPCC, 2001). This trend might be due to a number of causes, such as changes in atmospheric moisture, thunderstorm activity and large-scale storm activity.

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According to the same estimates, cloud cover increased by 2% over middle and high latitude land areas, and in some regions this trend could be related to the observed decrease in diurnal temperature range.

The effects of climate warming are of major importance in areas subject to ice or snow cover. In such sensitive areas, even a small temperature change can profoundly affect the hydrological cycle and the extent in space and time of ice and snow cover (Wright & Schindler, 1995). These areas also usually have the lowest availability of instrumental records of temperatures and other meteorological parameters.

One of the most important Italian database is that provided by the Meteorological Service of the Italian Air Force (Jones, 1995). Recently Brunetti & *alii* (2000) analysed the daily temperature series of 27 stations located throughout Italy, using a national database run by the Ufficio Centrale Ecologia Agraria (UCEA) in Rome. The increasing trends of minimum and maximum temperatures were without exception significant, with the greatest contribution to the positive trend coming from the last 20 years at the stations located in Northern Italy (Brunetti & *alii*, 2000).

Unfortunately, all the stations run by the UCEA were located at low altitudes and none of them was representative of the subalpine or alpine area. Climate change during the last century at high elevation sites has been analysed by several authors, mainly using data from Swiss, German and Austrian stations run by the respective national weather services e.g. Beniston & *alii*, 1997; Böhm & *alii*, 2001; Weber & *alii*, 1994; 1997. These studies show that temperatures increased at high-elevation mountain sites by 1-2 °C in the last century and that minimum temperatures rose faster than maximum temperatures (Beniston & *alii*, 1997). Data from high altitude stations showed a similar increase in daytime and night-time temperatures, so that no diurnal asymmetry was observed for these sites (Weber & *alii*, 1994).

For precipitation, too, the information available for mountain areas is rather limited. There is one long-term (since 1817) data series referring to the station of Gran S. Bernardo, located on the main ridge of the Alps at 2479 m a.s.l. An analysis of precipitation amount at this site during the last century showed an increase in winter precipitation since the 50s and an overall increasing frequency of heavy rain (Ambrosetti & *alii*, 1990).

Data collected at eleven meteorological stations in North-Western Italy were used to assess temperature and precipitation trends at medium and high altitudes in the Alpine area. Nine of these stations, located in the Ossola Valley (fig. 1), have been run by the National Electric Power Agency (ENEL) since 1920-30. A total of 30 stations were operative in this area for various periods, but only at nine sites were data recorded continuously. As a consequence, only data from these sites were tested for trends. Two other stations located in the same area were included in the analysis: Pallanza, run by the Institute of the Ecosystem Study of the CNR, and Domodossola, run by the Collegio Mellerio Rosmini.

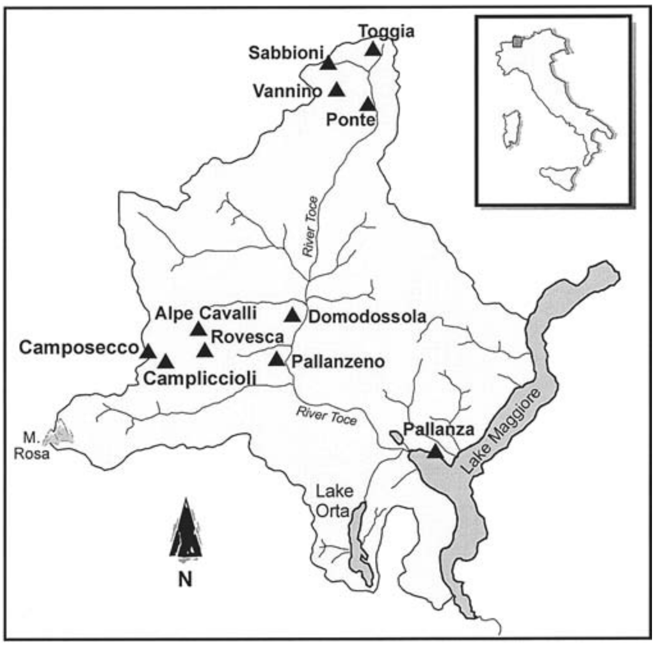

FIG. 1 - The Ossola Valley with location and altitude (m a.s.l.) of the meteorological stations.

STUDY AREA, DATA AND METHODS

The station of Pallanza is located in the town of the same name (200 m a.s.l.; fig. 1, tab. 1), on the shore of Lake Maggiore. Its location means it has a climate typical of the Northern Italian deep subalpine lakes (Maggiore, Como, Lugano, Iseo, Garda): mild winters and low annual thermal excursion (Mennella, 1970). The influence of the lake, however, is strictly limited to the shore area, and decreases with distance from the lake.

The other stations are all in the Ossola Valley, at different altitudes (from a minimum of 240 m a.s.l. to above 2000 m a.s.l.) (fig. 1). The Ossola Valley is located in the South-Western (Pennine and Lepontine) Alps between 45° 56' and 46° 28' North, 7° 50' and 8° 30' East. It has a total area of about 1532 km^2 (2.9% covered by glaciers). It is closed to the N, NE and NW by the Alps, with a divide of between 2500-3000 m; the highest peak is Mount Rosa (4633 m), the mean altitude 1690 m. The watershed is open to the South towards Lake Maggiore and the Po Valley. The main axis of the valley, oriented approximately NS, is the course of the river Toce, which is fed by streams from several lateral sub valleys before reaching Lake Maggiore.

It is a well-known fact that the southern side of the Alps is characterised by a strikingly different climatological pattern from that of the northern side: higher temperature, higher number of sunny hours, fewer rainy days, but generally more intense precipitation. These differences are due to the fact that the southern slopes are shielded by the mountains from the air masses of marine origin which affect Central Europe. Usually wet winds coming from the

TABLE 1 - Main characteristics of the meteorological stations and available data. P: precipitation, HS: snow depth

Station	Latitude N	Longitude E	Altitude m a.s.l.	Starting year	Used data frequency	Mesured data at each site	Managing institution
Pallanza	45.92	8.54	200	1971	Monthly	Tmin, Tmax, P	CNR ISE
Pallanzeno	46.05	8.25	240	1971	Monthly	Tmin, Tmax, P	ENEL
Domodossola	46.06	8.12	270	1946	Daily	Tmin, Tmax, P	Collegio Rosmini
Rovesca	46.06	8.12	820	1935	Daily	Tmin, Tmax, P, HS	ENEL
Ponte	46.37	8.43	1300	1935	Daily	Tmin, Tmax, P, HS	ENEL
Camplicciòli	46.05	8.07	1320	1971	Monthly	Tmin, Tmax, P	ENEL
Cavalli	46.09	8.11	1500	1935	Daily	Tmin, Tmax, P, HS	ENEL
Vannino	46.39	8.37	2180	1935	Monthly	Tmin, Tmax, P	ENEL
Toggia	46.44	8.43	2200	1935	Daily	Tmin, Tmax, P, HS	ENEL
Camposecco	46.06	8.05	2281	1935	Monthly	Tmin, Tmax, P	ENEL
Sabbioni	46.42	8.35	2460	1935	Monthly	Tmin, Tmax, P	ENEL

Atlantic do not directly affect the Lake Maggiore area and the valleys located North-West of the lake, and so do not bring precipitation to the region. The dominant meteorological pattern determining the major precipitation in the subalpine area is produced by air masses coming from the South (SW to NE) and climbing over the Alps. In contrast, the air masses coming from the North generally cause precipitation only in a the area close to the border, in the Northern part of the Ossola Valley (Val Formazza) (Kappenberger & Kerkmann, 1997).

When moist air masses cross the Po plain, they produce intense orographic precipitation on colliding with the first of the high ground. The intensity of this precipitation is accentuated in this area by the absence of pre-alpine foothills. Consequently, the Ossola valley shows strong gradients in the amount of precipitation, with the highest volumes in the South (1800-2000 mm) and a lower amount in the North (1400-1600 mm) (Carollo & *alii*, 1989).

The alpine character of the area and its abundance of water resulted in the construction of several hydroelectric power schemes. The schemes were first built in the early XX century, and their development underwent a massive extension between the two World Wars (Chiaramonte, 1985; ANIDEL, 1961). Most of the dams were permanently staffed by operators who also performed meteorological measurements based on regional programmes run by the Companies managing the schemes. This work has yielded long term data sets referring to remote sites in the Valley, in most cases of excellent quality. Other valuable data were collected at the station of Domodossola, which was managed by the Collegio Mellerio Rosmini as part of the Italian Meteorological Network from 1867 to 1980. Data for the period after this date were however collected and validated using proper modern methods (Mosello & *alii*, 2001). The whole data series of air temperature has been discussed elsewhere (Lami & *alii*, 2002). Only data collected since 1946 (after the interruption caused by the Second World War) are considered here (fig. 1).

Minimum (Tmin) and maximum (Tmax) temperature and precipitation volume (P) were measured daily at all the stations considered for the study. However, daily data for only five stations were available for elaboration in electronic format (Excel spreadsheet); only the monthly mean values were used in the other cases. Data from six sites cover the period 1971-2000; measurement at the others started in the 30s-40s (fig. 1). Snow cover data were analysed only for the high altitude site of Toggia, to investigate the effect of climate warming on snowpack dynamics.

Before any statistical analysis was performed, we checked whether the reported minimum of a day or a month was smaller than the maximum. Then the annual means of Tmin and Tmax for all pairs of data series were compared to reveal any discrepancies in the records.

Mean temperatures (Tmed) were calculated from minimum and maximum values (Tmed = (Tmin + Tmax)/2). The diurnal temperature range (DTR) was calculated as the difference between Tmax and Tmin. Monthly, annual and seasonal means were calculated from the measured values. We regarded the seasons as follows: winter (January-March), spring (April-June), summer (July-September), autumn (October-December). Temperature anomalies were calculated for the monthly data as departure from the pluriannual mean values.

Trend analysis was performed on monthly blocks of data, both of Tmin and Tmax, using the Seasonal Kendall Test (SKT; Hirsch & *alii*, 1982); this applies a correction which takes the seasonality of the data into account. The Mann Kendall Test (KT; Kendall, 1975) was applied to the seasonal mean values. In addition to the level of significance of the trends, the slope values were calculated according to SEN (1968) and used to determine the temperature changes (ΔT) during the study period.

RESULTS AND DISCUSSION

Temperature

All the stations are clearly affected by the presence of the mountains, and the dominant factors determining the climatic characteristics are altitude and exposure; the orientation and shape of the valleys where the stations are locat-

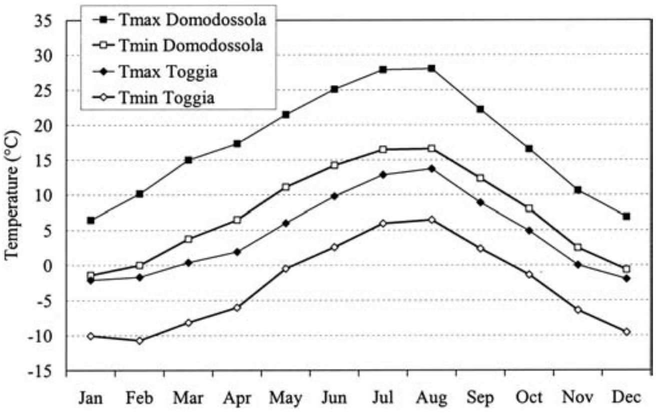

FIG. 2 - Mean monthly values of Tmin and T max at Domodossola (277 m a.s.l.) and Toggia (2200 m a.s.l.) (mean values of the last 10 years).

ed are also of major importance. As an example of seasonal temperature variations, the mean monthly values of two stations, one located on the valley bottom and one at high altitude, are shown in figure 2. The temperature range (the difference between mean maximum and minimum temperatures of each month) is wider at the lower site, where it reaches about 10 °C in the summer months (fig. 2).

The results of the trend analysis performed on the temperature data for the period 1971-2001 are shown in table 2. All the stations showed a highly significant positive trend of Tmin in the last 30 years. Tmax did not change significantly at the high-altitude sites of Toggia, Camposecco and Sabbioni; it decreased slightly at Pallanzeno, and increased markedly at the other sites (tab. 2). Trend slopes were always high and ranged between 0.03-0.04 C° per year (Tmin, Ponte and Cavalli) and 0.10-0.16 °C per year (Rovesca). Trends proved to be more significant at lower sites, and mainly affected the spring and summer temperatures. Only some low-altitude sites showed a significant positive trend in autumn and winter. The Camposecco station, located above 2300 m a.s.l., yielded a contrasting result: a negative Tmin trend and a positive Tmax trend were detected in winter. It was the summer Tmin that was usually subject to the warming effect at the sites located above 2000 m a.s.l. (tab. 2). The mean annual values of Tmin and Tmax at three selected sites, representative of different altitude levels, are shown in figure 3. In all

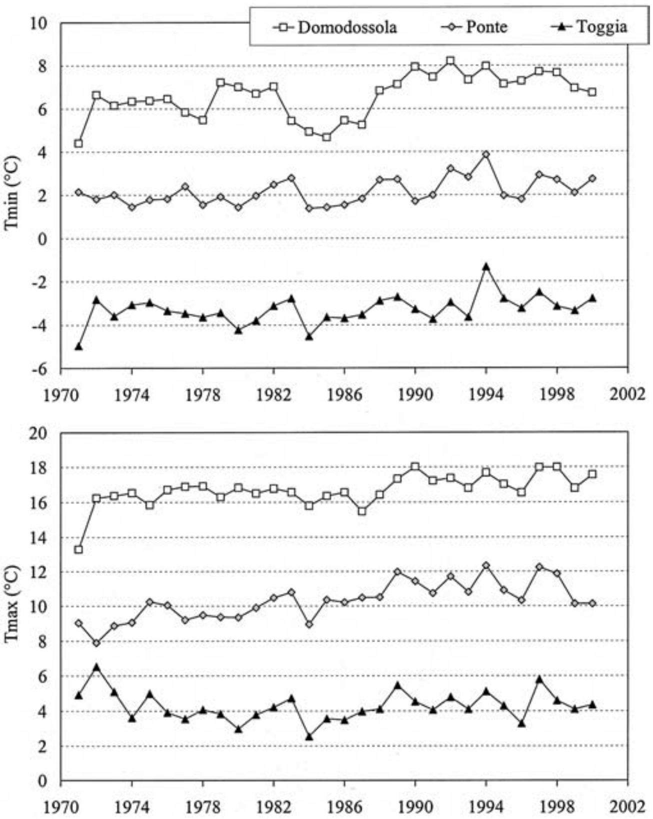

FIG. 3 - Trends of Tmin (above) and Tmax (below) at four different sites in the last 30 years.

TABLE 2 - Results of the Seasonal Kendall Test (SKT) applied to monthly temperature data and of the Kendall Test (KT) applied to seasonal data. Level of significance: * p<0.05; ** p<0.01; *** p<0.001; n.s. not significant; b: trend slope. For all the stations the period considered is 1971-2000

	SKT				KT															
	Monthly data				Winter				Spring				Summer				Autumn			
	Tmin		Tmax		Tmin		Tmax		Tmin		Tmax		Tmin		Tmax		Tmin		Tmax	
	sign	b	sign	b	sign	b	sign	b	sign	b	sign	b	sign	b	sign	b	sign	b	sign	b
Pallanza	***	0.05	***	0.06	n.s.	0.02	**	0.06	***	0.06	***	0.10	***	0.06	***	0.08	**	0.05	n.s.	0.04
Pallanzeno	***	0.08	*	-0.03	n.s.	0.02	n.s.	0.04	***	0.02	n.s.	-0.04	**	0.10	**	-0.10	***	0.09	n.s.	-0.03
Domodossola	***	0.06	**	0.04	n.s.	0.03	*	0.06	**	0.06	**	0.06	*	0.05	n.s.	0.01	**	0.06	n.s.	0.03
Rovesca	***	0.10	***	0.17	n.s.	0.04	***	0.12	***	0.11	***	0.21	***	0.12	***	0.18	***	0.09	***	0.14
Ponte	***	0.03	***	0.09	n.s.	0.01	*	0.06	**	0.06	***	0.12	*	0.02	***	0.12	n.s.	0.02	n.s.	0.02
Campliccioli	***	0.13	**	0.03	n.s.	0.05	***	0.15	*	0.06	***	0.21	**	0.05	***	0.14	n.s.	-0.02	n.s.	0.02
Cavalli	**	0.03	***	0.07	n.s.	-0.02	n.s.	0.01	*	0.04	***	0.15	*	0.04	***	0.07	n.s.	0.03	n.s.	0.03
Vannino	***	0.06	***	0.05	n.s.	0.01	n.s.	0.03	**	0.07	**	0.09	***	0.08	***	0.08	n.s.	0.04	n.s.	-0.01
Toggia	**	0.04	n.s.	0.01	n.s.	0.00	n.s.	0.01	n.s.	0.02	n.s.	-0.10	***	0.07	n.s.	0.03	n.s.	0.02	*	-0.05
Camposecco	**	0.03	n.s.	0.03	**	-0.09	**	0.06	***	0.10	n.s.	0.03	***	0.09	**	-0.06	n.s.	0.03	*	-0.07
Sabbioni	***	0.05	n.s.	0.02	n.s.	0.01	n.s.	0.18	*	0.06	n.s.	0.04	*	0.06	*	0.07	n.s.	0.03	n.s.	-0.02

TABLE 3 - Results of the Seasonal Kendall Test (SKT) applied to monthly temperature data of the period 1930-2001. Level of significance: * p<0.05; ** p<0.01; *** p<0.001; n.s. not significant; b: trend slope

Station	Period	SKT Tmin		SKT Tmax	
		sign	b	sign	b
Domodossola	1942-2001	***	-0.020	***	0.017
Rovesca	1929-2001	**	0.009	n.s.	0.006
Ponte	1934-2001	n.s.	-0.003	n.s.	0.006
Cavalli	1930-2001	*	-0.007	**	-0.007
Toggia	1935-2001	*	-0.009	***	0.014

cases the warming effect has been particularly evident in the last 10-15 years. This result is in agreement with the general picture of the climate trend in Italy over the last 20 years given by Giuliacci & *alii* (2001).

The longer data series available for 5 stations since the 30s were also tested for trends (tab. 3). They showed a more heterogeneous pattern compared to the 30-year trends: only at Domodossola and Toggia was a highly significant positive trend detected for Tmax. Tmin decreased at all the sites with the exception of Rovesca, in contrast with the overall increase recorded during the last 30 years (tab. 2). At Cavalli both Tmin and Tmax decreased if we consider the whole data series (tab. 3), while they increased significantly in the most recent period (tab. 2). At Rovesca, the increase of Tmax was not detected in the 70-year period (tab. 3), while it was highly significant and characterised by a steep slope since the 1970s (tab. 2). These results pointed to the evidence of a sharp temperature increase in the last 3 decades. The long-term trend of temperature values (as departures of Tmed from the long-term mean of the period 1930-2001) is shown in figure 4. All the stations were characterised by a cold period between 1932 and 1942. Thereafter, temperatures increased sharply in the middle 1940s, reaching the maximum values for the whole period. Between 1945 and 1970 temperatures displayed a marked decreasing trend, which was followed by the sharp increase of the last 30 years.

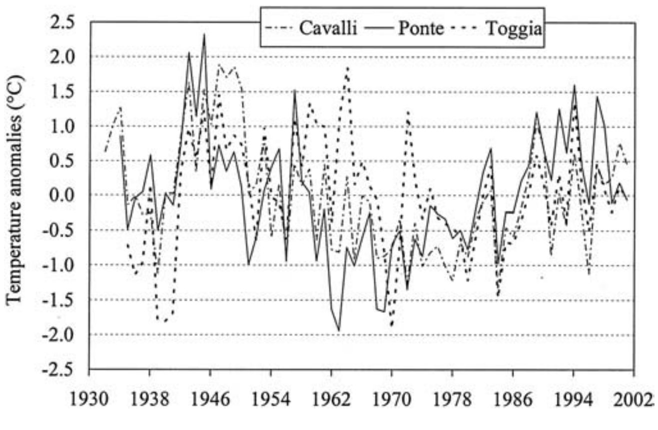

FIG. 4 - Anomalies of Tmed as departure form the long-term mean (1930-2000) at three different sites.

Both of the statistical tests described here can only detect monotonic trends within time series. Because of the contrasting trends of temperature during different periods in the last 70 years, a univocal trend cannot be detected at the study sites. On the other hand, a common pattern did emerge from the analysis of the most recent data series, even though Tmin and Tmax were not affected by the warming in the same way. The different behaviour of Tmin and Tmax trends lead to a significant change over time of DTR values. This parameter was calculated for four sites with data available on a daily basis (tab. 4). A significant positive trend was recorded at Rovesca, Cavalli and Ponte (+0.04/0.07 °C y^{-1}), due to the more marked increase of Tmax compared to Tmin, while DTR decreased slightly at the high altitude site of Toggia (–0.02 °C y^{-1}), where only Tmin has increased significantly in the last 30 years (tab. 4). This is in contrast with the results reported by Weber & *alii* (1994) for some mountain and midland stations in Central Europe: in their study, only the low-lying stations showed asymmetric diurnal temperature change, owing to a significant positive trend of Tmin and no significant trend of Tmax. Nevertheless, because any change in DTR is a combination of several factors (large-scale warming, variations in cloud cover and aerosol optical depth), it can reasonably be hypothesised that DTR changes are subject to regional differences (Weber & *alii*, 1997).

The increase in mean air temperature (ΔT) over the whole climatological record (30 years) was calculated for the various sites and related to their altitudes (fig. 5). As previ-

TABLE 4 - Trend of DTR values in the last 30 years at four sites. b: regression slope. Units: °C y^{-1}. Level of significance: * p<0.05; ** p<0.01; *** p<0.001; n.s. not significant

Station	sign	b
Rovesca	***	0.06
Ponte	**	0.07
Cavalli	*	0.04
Toggia	n.s.	-0.02

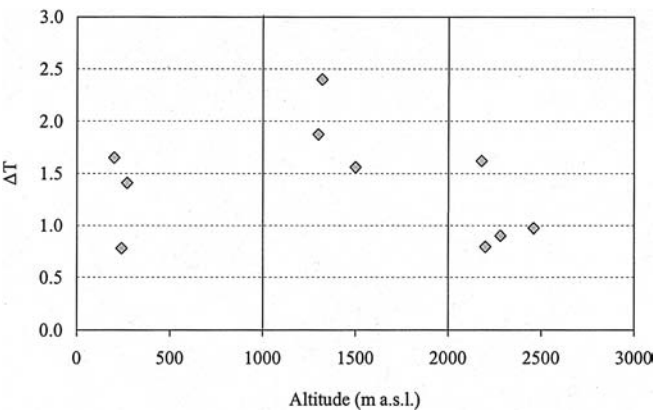

FIG. 5 - Relationship between the increase of mean air temperature (ΔT) at the sampling sites in the period 1971-2001 and their altitudes.

ously discussed, the warming seems to have mainly affected the sites located at medium altitude (1000-1500 m a.s.l.), where the overall temperature increase was between 1.6 and 2.4 °C. At lower altitudes (< 1000 m a.s.l.) ΔT was between 0.8 and 1.7 °C while above 2000 m a.s.l. it was about 1.0 °C, with the exception of the station of Vannino (1.6 °C).

Precipitation

The SKT and the KT were applied respectively to the monthly and seasonal data of precipitation volume, to detect trends (tab. 5). Pallanzeno was excluded from the analysis owing to several interruptions in the data record. Rovesca was the only station showing a significant decreasing trend ($p<0.001$; b –1.5 mm/year), in summer and winter. Even when they were not significant, the precipitation trends were negative in winter and positive in autumn at most of the sites (tab. 5).

This result is in agreement with the data elaborated by Buffoni & *alii* (1999). The authors found decreasing trends of precipitation on a yearly basis using data from 32 stations over the whole of Italy; the trends were statistically significant however only in Central-Southern Italy.

Giuliacci & *alii* (2001) reported a general decrease (14%) of precipitation volumes in Italy in the last 20 years, a situation which was more marked in the North (–18%). The decrease did not occur in all the seasons in the same way: for example, in autumn precipitation increased by 11% (40% in the North). The number of rainy days also increased in autumn (9.5% and 6% for the whole of Italy and for the North, respectively), but to a lesser extent than precipitation volume (Giuliacci & *alii*, 2001). This finding leads to the hypothesis of an intensification of rainy events, with higher daily precipitation volumes.

Brunetti & *alii* (2001) observed an increase in heavy precipitation together with a decrease in total precipitation; this signal was particularly evident in North-Western Italy. Italy. Ambrosetti & *alii* (1990) also found an increase in the number of stormy events (more than 100/150 mm per day) in the area of Canton Ticino (Switzerland) starting from the middle of the 70s. They suggested the increasing frequency of anticyclonic blockings south of the Alps recorded in the last two decades as the main explanation for the observed trends (Ambrosetti & *alii*, 1990).

To test this hypothesis in the study area, we averaged the yearly data of precipitation amount and number of days with rain (> 1 mm) of three different sites (Rovesca, Ponte, Toggia) and plotted them in figure 6. Both the two series showed a decreasing trend, but this proved to be significant only for the latter variable, which trend was more steeply in the last 10 years (fig. 6). These results

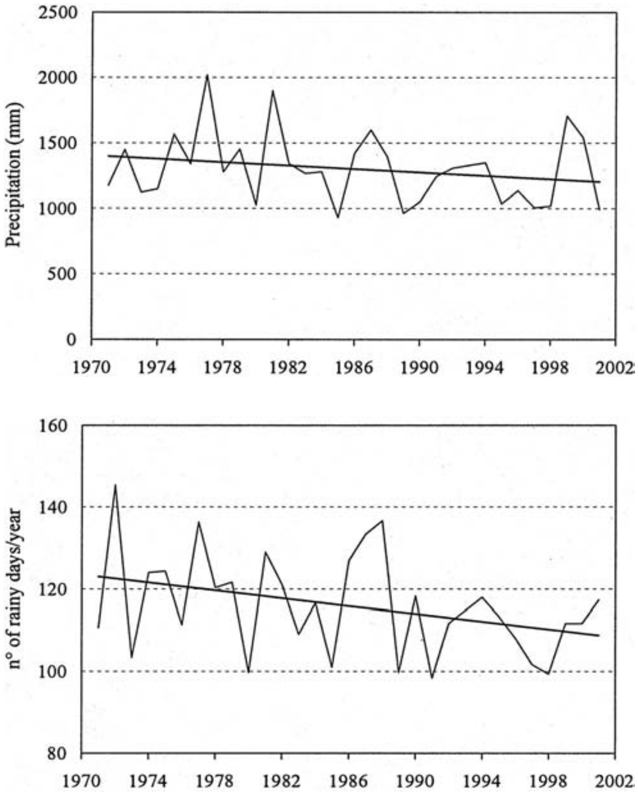

FIG. 6 - Trends of precipitation amount (above) and number of rainy days per year (below) in the last 30 years. Average values of three different sites: Rovesca, Ponte, Cavalli.

TABLE 5 - Results of the Seasonal Kendall Test (SKT) applied to monthly data of precipitation volume and of the Kendall Test (KT) applied to seasonal data. Level of significance: * $p<0.05$; ** $p<0.01$; *** $p<0.001$; n.s. not significant; b: trend slope. For all the stations the period considered is 1971-2000

	SKT		KT							
	Monthly data		Winter		Spring		Summer		Autumn	
	sign	b	sign	b	sign	b	sign	b	sign	b
Pallanza	n.s.	-0.08	n.s.	0.12	n.s.	0.12	n.s.	2.68	*	-2.88
Pallanzeno	–	–	–	–	–	–	–	–	–	–
Domodossola	n.s.	-0.59	n.s.	-0.21	n.s.	-0.62	n.s.	-1.51	n.s.	0.75
Rovesca	***	-1.50	*	-1.81	n.s.	-2.27	*	-2.36	n.s.	-1.33
Ponte	n.s.	-0.18	n.s.	-0.87	n.s.	-0.31	n.s.	-0.36	n.s.	1.13
Campliccioli	n.s.	-0.17	n.s.	-0.74	n.s.	0.44	n.s.	-0.93	n.s.	2.31
Cavalli	n.s.	0.55	n.s.	-0.80	n.s.	0.94	n.s.	0.63	n.s.	2.28
Vannino	n.s.	0.16	n.s.	-0.29	n.s.	0.72	n.s.	-0.01	n.s.	1.10
Toggia	n.s.	-0.40	n.s.	-0.28	n.s.	0.30	n.s.	0.17	n.s.	0.52
Camposecco	n.s.	0.05	n.s.	-0.44	n.s.	-0.28	n.s.	0.21	n.s.	1.46
Sabbioni	n.s.	0.38	n.s.	0.11	n.s.	0.56	n.s.	0.67	*	2.42

point to a general tendency towards more intense precipitation events in the last few years; however, the same analysis would have to be performed on a higher number of sites to yield more reliable results.

Snow depth

Snow depth data have been available on a daily basis since the 30s for the station of Toggia (fig. 1, tab. 1). Figure 7 shows the long term trend of snow depth (mean annual values) and duration (days per year with snow) at this site. Snow depth has gradually decreased since 1932, notwithstanding periodic fluctuations. The main change occurred in the mid 60s, when mean snow depth values fell from about 110 to 90 cm (fig. 7). On the other hand, the total amount of precipitation has not changed in the whole period. The duration of snow cover did not show a univocal trend, but decreased form 1932 to 1950, then increased until the mid 1980s, decreasing again during the last 15 years (fig. 7). Snow reduction seems to be most pronounced in the most recent period (1985-2000), both in terms of amount of snow and its duration in time.

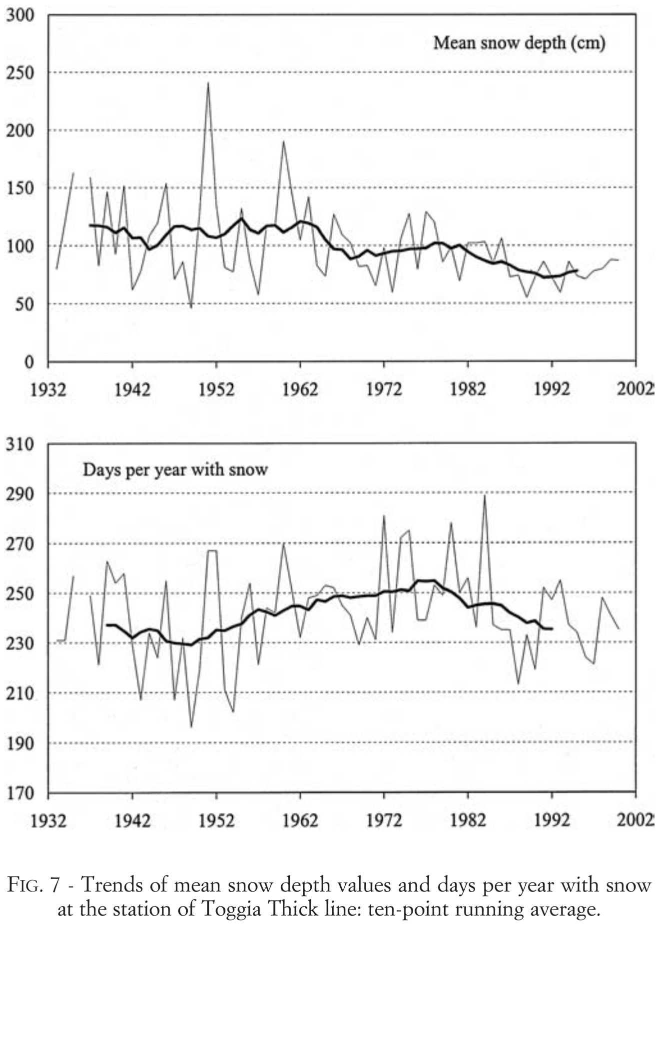

FIG. 7 - Trends of mean snow depth values and days per year with snow at the station of Toggia Thick line: ten-point running average.

CONCLUSIONS

Mountain areas represent about 20% of the earth's continental areas. They are of paramount importance as key elements of the hydrological cycle and essential water resources for lowland regions. Any spatial or temporal change in climate, especially in precipitation regime, would heavily affect mountain ecosystems, which are characterised by a high level of biodiversity, and impact on the river systems originating in mountainous areas. The difficulties of investigating and understanding climatic patterns in mountain regions arise primarily because of a lack of observational data. Such data as are available are usually inadequate for meteorological investigations in areas with complex topography. As a consequence, currently used general circulation models often fail to represent the climatic features of mountain areas. On the other hand, meteorological stations at high elevation or in remote areas are not affected by urbanization and hence are of invaluable importance in large-scale studies of atmospheric features.

While the stations considered in our study are located in a limited geographical area, they cover an altitudinal range from 200 to about 2500 m a.s.l., and are representative of conditions both in high-altitude remote areas and in the surrounding lowlands. There was also no direct anthropogenic impact, such as the effects of urbanization, on any of the low-lying stations apart from Pallanza. Furthermore, the location of the sites makes them representative of an area usually characterised by intense precipitation, mainly of orographic origin, so that they were suitable for the analysing the trends of precipitation amount and the occurrence of stormy events.

Climate warming mainly affected minimum temperatures. DTR analysis was performed only for a few sites and did not show a univocal trend; this was not surprising, as DTR values are affected by several factors, so that they are subject to wide changes on a regional scale. Cloudiness is probably the main factor determining different DTR trends under the same large-scale conditions (Weber & *alii*, 1997).

Trends similar to those presented here emerged from climatic records available for other stations in Italy. The Italian climate has become warmer and drier, especially in the South, since about 1930. In the last 50 years a positive air surface pressure trend has been present over Italy, determining an increase in the frequency of subtropical anticyclones over the Western Mediterranean basin (Brunetti & *alii*, 2000). Several studied have highlighted the sharp increase in temperature recorded after 1980, both in Italy (Giuliacci & *alii*, 2001; Brunetti & *alii*, 2000) and in Europe as a whole (e.g. Weber & *alii*, 1997).

Precipitation amount has not changed significantly at the study sites, while the number of rainy days per year has tended to decrease, especially in the last few years. This result partly confirms the hypothesis that more intense precipitation events are increasing in frequency (Brunetti & *alii*, 2001). Trends of precipitation volume were positive, if not significant, in autumn, usually the highest flood risk season. This result is quite striking, though admittedly the data of only a few sites have been analysed. The analysis should be extended to more sites for higher-confidence results to be attained.

The analysis of long-term data series of snow depth at a high altitude site showed the impact of climate warming in the area. The reduction of snow depth has been continuous since the 1930s, while a distinct decrease of snow duration has been recorded in the last 15 years. The fact that wider areas are not being covered by snow but are being exposed to weathering processes affects the export of solutes from the catchments of lakes and streams, with consequences for the chemistry of surface waters (Sommaruga-Wögrath & *alii*, 1997; Rogora & *alii*, 2003). Furthermore, snowmelt episodes may become more frequent in winter, altering the typical pattern of snow accumulation followed by melting in spring (Wright and Schindler, 1995).

The analysis of both temperature and precipitation data at the study sites showed how local differences may have some impact on climatic regime. Local climatic changes may differ considerably from the general trends, due to several factors, such as altitude, exposure, orientation and shape of the valleys. As a consequence, results obtained from the analysis of meteorological data at a limited spatial scale should be considered with caution, because they may not necessarily be significant indicators of large-scale variations. Nevertheless, the data considered in this study have given a reliable indications of how climatic features vary with altitude range. They have also allowed a preliminary investigation of the change in precipitation regime which has been occurring in the north-western subalpine area, one of the most flood-prone areas in Italy.

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