Vol. 31: 217–225, 2006 | CLIMATE RESEARCH Clim Res | Published July 27

Observed temperature changes in Emilia-Romagna: mean values and extremes

R. Tomozeiu[1,*], V. Pavan[1], C. Cacciamani[1], M. Amici[2]

[1]ARPA-Servizio IdroMeteorologico Regionale, Viale Silvani 6, 40122 Bologna, Italy

[2]*Present address:* Centro Funzionale Protezione Civile Regione Marche,Via Cameranense 1, 60029 Passo Varano, Italy

ABSTRACT: Temporal and spatial variability of temperature in Emilia-Romagna is described using daily maximum and minimum temperature at 40 stations covering the period 1958 to 2000. Before use, data were quality controlled and tested for inhomogeneity using standard techniques. First, a description of climatological values of maximum and minimum temperature and of their temporal variability is given. Then, frequency of extreme events in temperature is described using 4 indices: 10th percentile of minimum temperature, 90th percentile of maximum temperature, number of frost days and heat wave duration. These indices are based on daily temperature and were computed for all seasons. For each season and each index, the magnitude of trends was estimated by linear regression, while statistical significance was evaluated by Kendall's τ. The analysis reveals the presence of an increase in mean maximum and minimum temperature, especially during winter and summer. Trends were significant in the plain and hill area. Similar tendencies were also observed in the 10th percentile of daily minimum temperature in both seasons, accompanied by a reduction in the number of frost days during winter. Positive trends were detected in the 90th percentile of daily maximum temperature during winter, spring and summer, leading to an increase in the heat wave duration index. These results were significant over almost the whole region, summer being the season characterised by the greatest number of stations with significant trends. The spatial variability of frequency of extreme events was analysed using cluster techniques. Finally, the relationship between winter frequency of extreme temperature events in Emilia-Romagna and large-scale Euro-Atlantic circulation patterns is briefly described. The results show the presence of significant values of correlation with some of the patterns considered, namely the Eastern Atlantic and European Blocking pattern.

KEY WORDS: Observed climate extremes · Indices of extremes · Temperature · Trends · Circulation patterns

1. INTRODUCTION

During the last century, observed surface temperature has undergone significant changes. In particular, from the late 19th century to 1994, the global mean surface air temperature increased from 0.3 to 0.6°C (Houghton et al. 1996). Analysing the trends in central Europe temperature, Brazdil et al. (1996) identified an increase in both maximum and minimum values during the period 1951–1990, more pronounced in the minima than in the maxima. Changes are not only observed in mean values, but also in the frequency of occurrence of extreme events and in their intensity, which are also important characteristics of regional climate. The importance of changes in frequency of extremes within the framework of climate change is due to the fact that they strongly influence the local ecosystems and society, and sometimes have destructive consequences for both. Thus, understanding how the extremes changed in the past and how they could change in the future—due to natural climate fluctuations or to anthropogenic factors—is very important. A study of the variability in occurrence of extreme temperature events at a global scale during the second half of the 20th century (Frich et al. 2002) shows the presence of a general increase in warm summer nights, a

*Email: rtomozeiu@arpa.emr.it

decrease in the number of frost days and a decrease in the intra-annual extreme temperature range. A similar study has been performed by Domonkos et al. (2003) for winter extreme low temperature events (EXCE) and summer extreme high temperature events (EXWE) during the 20th century, using 11 stations from southern and central Europe. This study reveals the presence of a negative tendency in EXCE frequency in the most recent decades, more evident in southern than in central Europe, and of a significant increase in EXWE frequency, especially in Krakow, Poland, and Prague, Czech Republic.

In Italy, the spatial and temporal variability of temperature extreme events have been little analysed, most studies being focussed on mean values of maximum, minimum and mean temperature on seasonal or annual time-scales (Cacciamani et al. 1994, Zuccherelli 1999-2000). Only Brunetti et al. (2001) analysed the frequency of temperature and precipitation extreme events during the last century in Italy. Brunetti et al. (2001) show that over the Italian peninsula climate is becoming warmer and drier, owing to an increase in frequency of heavy precipitation events and in the length of long dry spells. Unfortunately, the number of stations considered by their study is small, and this limits the strength of the results, especially with respect to precipitation extremes.

The aim of the present study is to describe temporal and spatial variability of temperature derived from observed station data from Emilia-Romagna, during the period 1958–2000. The link between winter large scale patterns and winter extreme temperature in Emilia-Romagna is also analysed.

The study is organised as follows. Section 2 presents the data-set and the extreme and circulation indices used. The methods used to analyse temporal and spatial variability of extremes are also presented. In Section 3, a description of climatological values of maximum and minimum temperature and of their temporal variability is given for all seasons. This is followed by the description of the temporal and spatial variability of extreme indices. The relationship between the winter variability of frequency of temperature extremes and Euro-Atlantic large-scale patterns is described in Section 4, and conclusions are presented in Section 5.

2. DATA AND METHODS

2.1. Data

Data used in this study are the time series of observed daily minimum and maximum temperature at 40 stations located in Emilia-Romagna. The region is depicted in Fig. 1, as is its orography (shading in Fig. 1b) together with its location within the Italian Peninsula (Fig. 1a). The data have been collected by the offices of Bologna and Parma of the former Italian Hydrographic Service (recently these offices have been transferred to ARPA-SIM) and cover the period 1958–2000.

Before analysis, the quality of daily data was checked (Pavan et al. 2003) and unreliable data identified and discarded. Cleaned data were used in order to obtain time series of monthly minimum and maximum temperature at each station, which were tested so as to identify the presence of inhomogeneities in the data using the standard normal homogeneity test (SNHT) developed by Alexandersson & Moberg (1997a,b). The SNHT for temperature is based on the assumption that the difference between temperature at the station being tested (test station) and at an 'ideal' reference station is fairly constant over time. In order to build the reference station time series, a weighted mean of a group of selected stations (those characterised by the highest correlation with the test station) was computed, the weights being the correlation coefficients between the test station and the reference station. The results provided by the statistical test were completed with information obtained from metadata.

Given that only a small number of stations did not pass the homogeneity test, and that no satisfactory

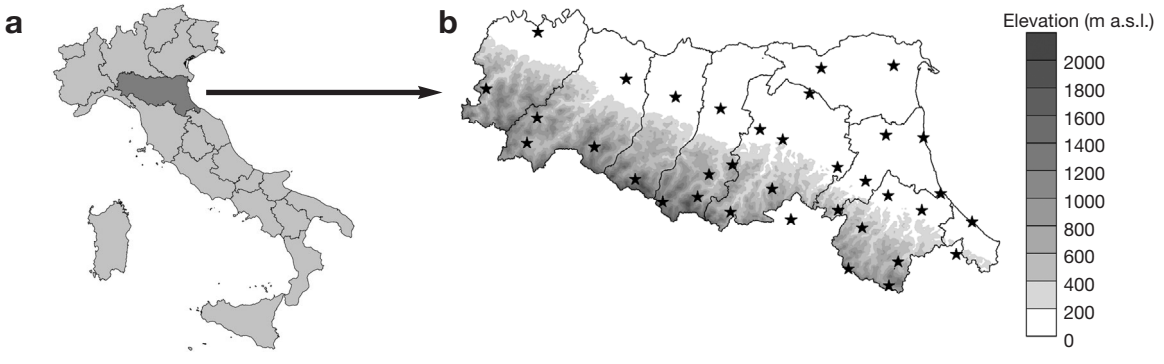

Fig. 1. Location of stations (★) used in this study. Shading represents height of orography

technique has yet been proposed in order to check the homogeneity of daily series and consequently adjust them (Wijngaard et al. 2003), all stations that presented significant inhomogeneity (as detected by the SNHT test and confirmed by metadata) were simply eliminated. In particular, these requirement were not met by 2 stations situated in the eastern part of Emilia-Romagna, so it was decided to remove these 2 from the data-set.

Finally, only stations with less than 20% missing data were retained. This condition, together with the results of the homogeneity of data, reduced the number of stations for which extremes were computed to 30 stations. The remaining stations are uniformly distributed over Emilia-Romagna.

2.2. Indices of extreme events

Extreme events are those events whose characteristics fall in the tail of the statistical distribution of all possible weather events. They are by definition rare, and can be identified in different ways e.g. as those events exceeding in magnitude some threshold, or as the maxima/minima of a variable over a certain period. In this study, the variability in frequency of occurrence of extreme events is described using 4 indices: 10th percentile of minimum temperature (T_{min10}), 90th percentile of maximum temperature (T_{max90}), number of frost days (F_d) and heat wave duration (HWD).

T_{min10} and T_{max90} were computed using the empirical distribution function with interpolation method as follows. Let n be the number of cases and 'p' the percentile value divided by 100. Express $(n-1)p$ as $(n-1)p = j + g$, where j is the integer part of $(n-1)p$, and g is the fractional part of $(n-1)p$. Then, if x_i is the value assumed during the ith event (after sorting), the percentile value is

$$x_{j+1} \quad \text{if } g = 0 \tag{1}$$

$$x_{j+1} + g\,(x_{j+2} - x_{j+1}) \quad \text{if } g > 0 \tag{2}$$

F_d is defined as the number of days with daily minimum temperature bellow 0°C, and HWD is the length in days of the period of at least 5 consecutive days in which $Tx_{ij} > Tx_{inorm} + 5°C$, where Tx_{ij} is daily maximum temperature at Day i of Period j, and Tx_{inorm} is the calendar day climatological value calculated for a 5 d window centred on each calendar day during a specified period.

The extreme indices were computed for each station, each season and for each annual regime during 1958–2000. Seasons were defined in the standard boreal format: winter as December to February (DJF); spring as March to May (MAM); summer as June to August (JJA); autumn as September to November (SON).

2.3. Large-scale circulation indices

Another data-set used in this study was that of the indices of the most relevant large-scale circulation patterns of the Euro-Atlantic region, namely the North Atlantic Oscillation (NAO), the Eastern Atlantic pattern (EA), the Scandinavian pattern (SCA) and the European Blocking pattern (EB).

The indices describing the temporal variability of the first 3 patterns were obtained by averaging over winter (DJF) the monthly time series available from NCEP at www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml. As documented in the referred web site, indices were computed following the technique suggested by Barnston & Livezey (1987), with the rotated principal components of monthly mean 700 hPa geopotential height anomalies for each calendar month included in the computation.

The EB index was obtained by applying the definition in Pavan et al. (2000a,b) to the NCEP/NCAR re-analysis 500 hPa daily geopotential height data available on a 2.5° × 2.5° regular grid.

2.4. Methods of analysis of temporal and spatial variability

All time series were analysed in order to detect the presence of time trends. The magnitude of trends was estimated by linear regression and its statistical significance using Kendall's τ (Press et al. 1986). This test is non-parametric and is more suitable when dealing with data that can assume only discrete values.

The spatial variability of extreme events was described by means of cluster analysis, performed for each index and season, in order to identify areas with similar temporal variability. Two clustering methods were applied in order to check robustness of results: complete linkage and Ward's methods (Wilks 1995). For each zone that resulted from cluster analysis, a winter extreme index was computed by area averaging single station indices. These indices are likely to be less affected by local random fluctuations in weather than single station indices, and this fact makes it easier to identify the presence of significant links between the occurrence of temperature extremes and of particular large-scale circulation patterns during winter.

3. CHANGES IN MINIMUM AND MAXIMUM TEMPERATURES AND THEIR EXTREMES

In the following, temperature variability is described, with particular focus on the presence of time trends. Analysis was firstly conducted on mean values and then on extreme event frequency indices.

3.1. Seasonal mean minimum and maximum temperature

The climatic characteristics of Emilia-Romagna are very peculiar, the region being surrounded in the southern part by the Apennines Mountains, and in the eastern part by the Adriatic Sea. The spatial distribution of the seasonal climatological values of minimum and maximum temperature for the period 1961–1990 follows the orography of the region, and is characterised by a northward positive gradient. The climatological values of seasonal minimum temperature vary between –3.7 and 2.1°C in winter and between 11.2 and 19.3°C in summer, while values of maximum temperature vary between 3.7 and 8.6°C in winter and between 20.5 and 29.5°C in summer.

A spatial mean of minimum and maximum temperature over all 30 available stations was computed for each season during the period 1958–2000. Then, the temporal variability of their time series was analysed. Positive trends were detected in both parameters for all seasons, but only the trend in minimum temperature for winter and autumn was significant ($p < 0.05$), while for maximum temperature positive trends were significant in all seasons. Fig. 2 presents the temporal variability of minimum and maximum temperature over the whole Emilia-Romagna during winter (Fig. 2a) and summer (Fig. 2b). The magnitude of trends in seasonal mean minimum temperature during 1958–2000 varied between 0.1°C decade^{-1} (spring and autumn) and 0.3°C decade^{-1} (summer). During winter, the increase in minimum temperature was around 0.2°C decade^{-1}. The increase in seasonal maximum temperature during 1958–2000 was greater than that in minimum temperature, its magnitude reaching values up to 0.4°C decade^{-1} in summer, winter and spring, and 0.2°C decade^{-1} in autumn. At the annual level, both parameters were characterised by positive trends, more significant and intense in the maximum temperature (about 0.4°C decade^{-1}) than in the minimum temperature (about 0.2°C decade^{-1}). Brazdil et al. (1996) found positive trends in the annual maximum and minimum central Europe temperature during the period 1951–1990; however, in this data-set the increase in the maximum was slightly smaller than that in the minimum temperature. The reason for the discordance between the results of Brazdil et al. (1996) and our results is the different length of the time series considered, because the last decade (1990–2000)—not included in Brazdil et al.'s (1996) data-set—had a great impact on the trend in our data.

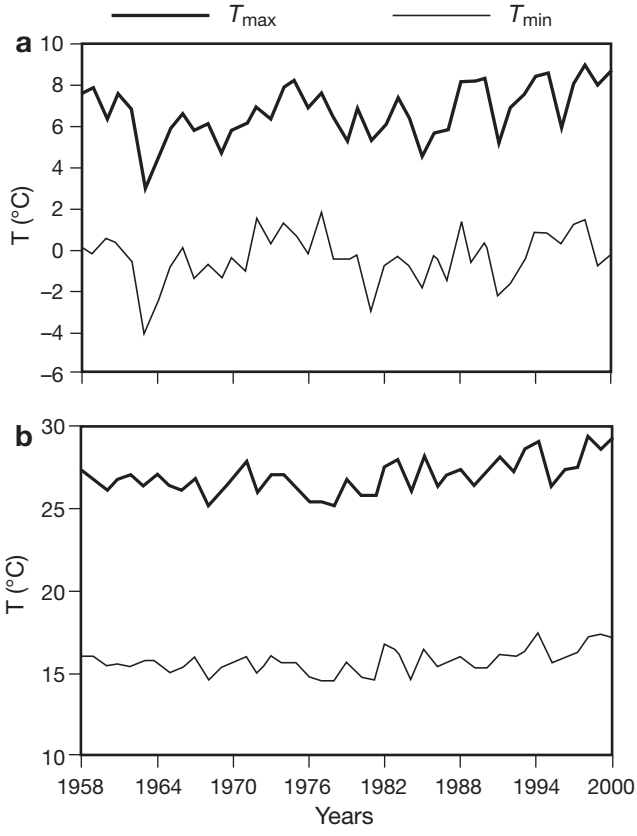

Fig. 2. Variability of Emilia-Romagna averaged minimum and maximum temperature during (a) winter and (b) summer

3.2. Changes in temperature extreme events

The above results provide evidence for the presence of some changes in seasonal mean maximum and minimum temperature. A rise in mean does not necessarily lead to a rise in temperature extreme events. In the following, we analysed the behaviour of extreme events as described by the 4 extreme indices defined in Section 2.

3.2.1. 90th percentile of seasonal maximum temperature (T_{max90})

The 90th percentile of maximum temperature increased in all seasons, significant results being observed in winter, spring and summer. Fig. 3 presents the spatial distribution of the 90th percentile of maximum temperature during winter (Fig. 3a) and summer (Fig. 3b), together with the associated trends (shaded area in °C season^{-1}) for the period 1958–2000. Mean values for the index are reported at each station, while circles indicate significant results. Fig. 3b shows that the increase in T_{max90} during summer is significant almost everywhere, with the exception of a few stations located over the mountains in the south-west, which were characterised by slightly negative trends. The other seasons presented significant positive trends

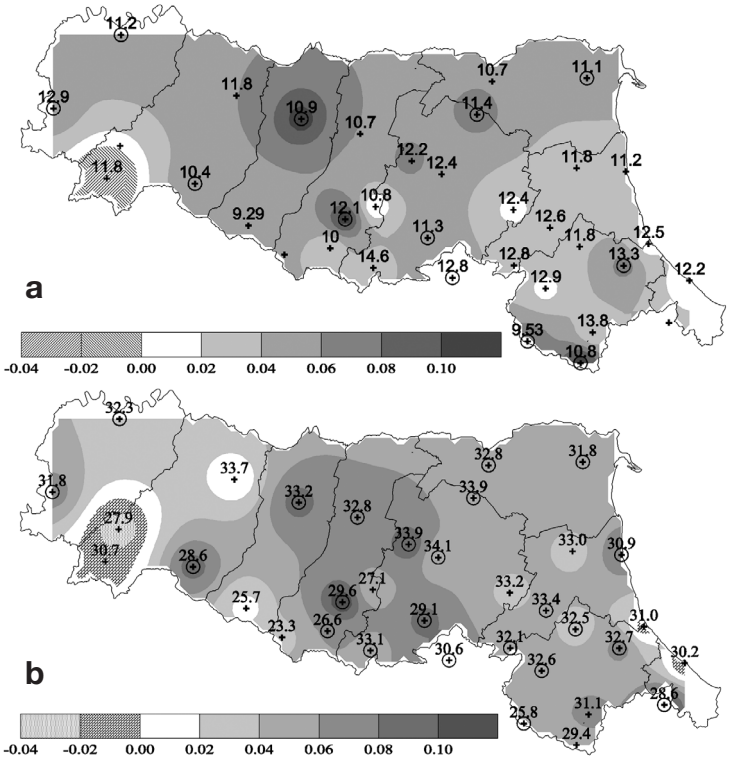

Fig. 3. Emilia-Romagna. T_{max90} during (a) winter and (b) summer. Mean values of the index are reported at each station; shading refers to intensity of trends (units per season or year); ⊕: significant results

and hill areas. Fig. 4 presents the spatial distribution of T_{min10} for winter (Fig. 4a) and summer (Fig. 4b) with the associated trend during 1958–2000. Both seasons present stations with negative trends of T_{min10}, the number of these stations being greater in summer than in winter. Comparison of trends in spatial distribution between T_{max90} and T_{min10} reveals that the positive trend of T_{max90} extends to the whole region in winter and summer, while the positive trend of T_{min} extend to the whole region during winter only.

As in the case of T_{max90}, the annual values of T_{min10} (ranging from –5.7°C to 1.3°C) present a pattern of trend more similar to that of summer, with positive and significant values in the plain and hill area.

3.2.3. Frost days (F_d) and heat wave duration (HWD) index

F_d and HWD are 2 very important indices from an agricultural point of view. Both indices were computed on seasonal and annual scale.

The increase in the winter value of T_{min10} (Fig. 4a) is associated with a decrease in F_d (Fig. 5). The pattern of winter F_d generally

only in the plain and hill area. The magnitude of trends of T_{max90} computed for the period 1958–2000 reaches values up to 1°C decade^{-1}. A comparison between this magnitude of increase and that of mean maximum temperature shows that the rate of increase in extreme event frequency is more pronounced than that in mean values.

The pattern of the annual trend of T_{max90} (not shown) presents a spatial distribution very similar to that of summer, due to the fact that maximum temperature increases more in summer than in winter.

These results are in agreement with those obtained by Frich et al. (2002), who analysed changes in extremes at the global level during the second half of the 20th century.

3.2.2. 10th percentile of seasonal minimum temperature (T_{min10})

Positive and significant trends were also obtained for T_{min10} during winter and summer (up to 0.9°C decade^{-1}), whereas spring was characterised by an only slightly positive trend. Autumn was characterised by a decrease in this index, especially over the mountains, and by a slight increase over plain

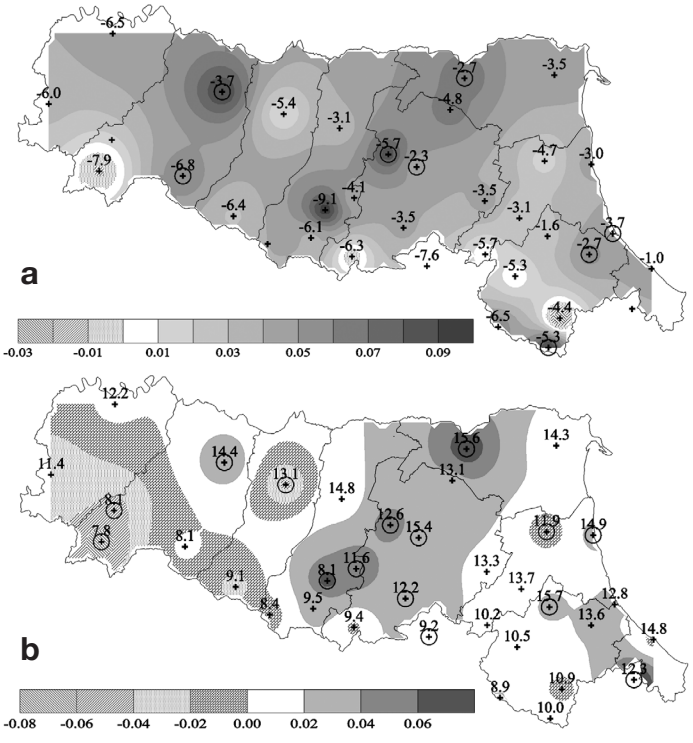

Fig. 4. Emilia-Romagna. T_{min10} during (a) winter and (b) summer. Mean values of the index are reported at each station; shading refers to intensity of trends (units per season or year); ⊕: significant results

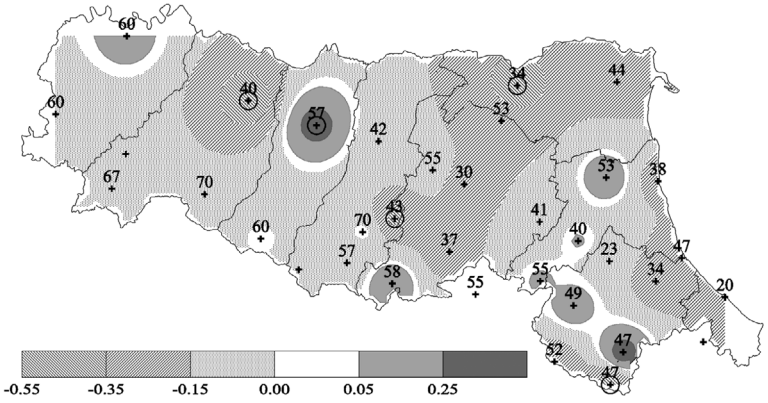

Fig. 5. Emilia-Romagna. F_d during winter. Mean values of the index are reported at each station; shading refers to intensity of trends (units per year); ⊕: significant results

reveals a decrease (up to 6 d decade^{-1}), with only a few stations located over the plain presenting slightly positive trends. Spring presents negative trends in most of the region, significant only at some stations, whereas autumn is generally characterised by slightly positive trends (not shown). The spatial distribution of the annual value of F_d (not shown) is influenced by those of winter and autumn, with a decreasing trend in most parts of Emilia-Romagna, reaching values of 8 d decade^{-1}. These results are in agreement with those obtained by Frich et al. (2002), who found for the annual number of frost days a near uniform decrease over the second part of the 20th century at the global level.

The heat wave duration (HWD) index presents positive trends in all seasons, more significant in winter, summer and spring. The trend is more intense in summer (Fig. 6), when it reaches a value of 5 d decade^{-1} and tends to cover the whole region. The summer pattern of HWD trend is very similar to that obtained for summer T_{max90}. Summer influences the HWD annual values, so that a positive and significant trend is detected in the annual value, with an increase reaching values up to 15 d decade^{-1}.

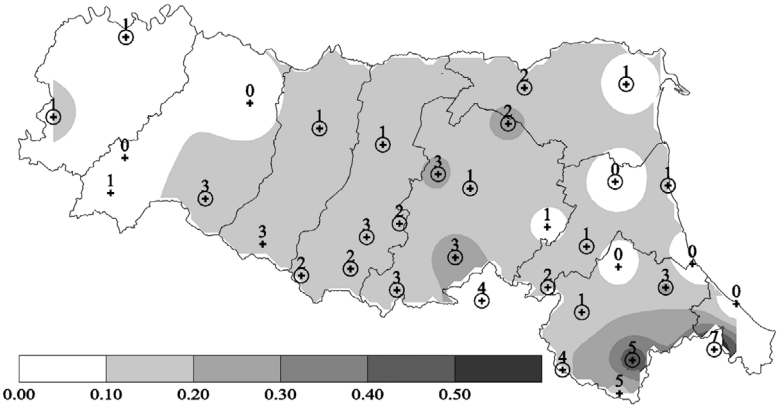

Fig. 6. Emilia-Romagna. HWD during summer. Mean values of the index are reported at each station; shading refers to intensity of trends (units per year); ⊕: significant results

The above results provide evidence for changes in extreme temperature events in Emilia-Romagna during 1958–2000, which are significant especially during winter and summer.

3.3. Spatial variability of extreme indices from Emilia-Romagna

Extreme events at a particular station are very sensitive to local weather fluctuations, which can be strongly influenced both by local physical processes and by purely random fluctuations. This can lower the significance of the correlation between extreme indices and other dynamical indices, such as large-scale circulation indices, and makes it very difficult to produce an analysis of the reasons behind changes in frequency of particular extreme events at a particular location, or to build statistical downscaling models in order to predict local changes in extreme event frequency.

In order to filter noise and single out the dynamical signal within the extreme indices time series, a cluster analysis was performed so as to identify areas with similar characteristics of temporal variability in temperature extremes. This analysis was separately applied to the seasonal time series of each index. Two methods of clustering were used: complete linkage and Ward's methods. Both methods provided similar results, suggesting robustness of the results. The number of clusters was different, depending on season and index considered. This number varied between 3 and 4 for winter and between 3 and 5 for the other seasons.

Cluster analysis of winter indices provides evidence for 3 zones for all indices except T_{min10}, for which 4 zones were identified. The zones are defined as follows:

- 'Apennine area' that includes the south-southwestern part of Emilia-Romagna
- 'Plain area' or 'Po valley' that includes the northern part of the region
- 'Eastern area' located in the eastern part of Emilia-Romagna, including stations close to the Adriatic sea and some stations from the plain.

Fig. 7 shows the clusters of winter extreme indices. Different symbols indicate stations belonging to different clusters. The Adriatic sea has a great influence on the distribution of T_{max90} and T_{min10} (Fig. 7a,b) but less on the distribution of F_d and HWD indices when stations

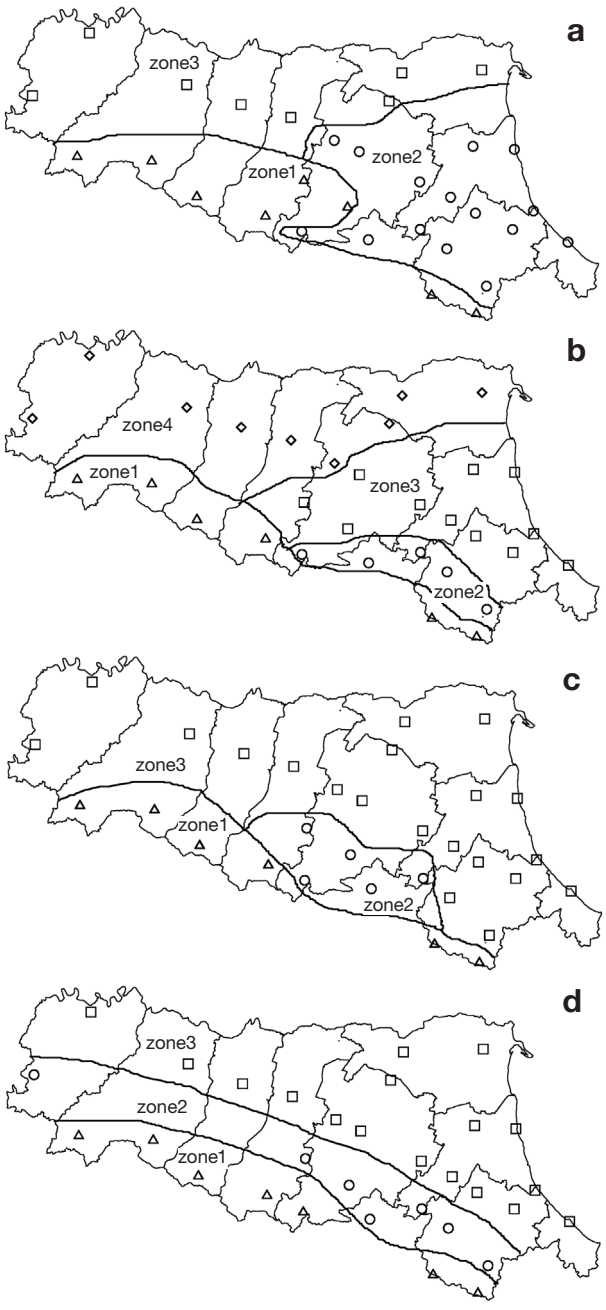

Fig. 7. Emilia-Romagna. Zones associated with different clusters of winter (a) T_{max90}, (b) T_{min10}, (c) F_d, and (d) HWD. △: Zone 1; ○: Zone 2; □: Zone 3; ◇: Zone 4

close to the sea are included in the plain cluster (Fig. 7c,d). The clusters generally reflect the influence of the orography and of the land-sea mask. Similar results were obtained by Galliani & Filippini (1985) and Cacciamani et al. (1994) who clustered winter daily Emilia-Romagna minimum and maximum temperature. A trend analysis was performed for each cluster and each index. Table 1 presents the trend coefficients.

Significant and positive trends in T_{max90} were present in Apennine area and Po valley clusters, which was more intense in the Po valley where it reached about 0.5°C decade^{-1}. The T_{min10} index was characterised by positive trends in all 3 clusters but significant only in the cluster located in the Eastern area. Concerning the other 2 indices, F_d presented a decrease in all clusters, which was not statistically significant. On the contrary, HWD was characterised by a positive trend in all clusters; in particular, a significant increase was obtained especially for the Plain area.

4. RELATIONSHIP BETWEEN TEMPERATURE EXTREMES AND LARGE-SCALE CIRCULATION PATTERNS IN WINTER

The relationship between the variability of extreme event indices and those of the main Euro-Atlantic large-scale patterns is described by means of a correlation matrix. Only results related to the winter season (DJF) are presented because it was expected that the large-scale circulation anomalies have maximum amplitudes during this season. Since most of the indices are characterised either by significant trends or by a strong variability over long time scales, only differenced time series were used. These series were obtained by computing the time series of DJF averages for each index and each cluster for the full period considered (1958–2000), and then by obtaining the differenced time series by subtracting the value of the previous year from each value. Results are shown in Table 2.

The link between large-scale patterns and local temperature extreme event frequencies depends both on the type of extreme and on the sub-region considered. The 2 patterns with the largest impact on temperature extremes were the EA and the EB. These 2 were very strongly linked to T_{max90} and F_d, and moderately linked to the other 2 indices. A moderate link is also noticeable between the SCA index and T_{min10} and F_d, while NAO seemed to have very little impact on the temperature extremes as far as internal variability is concerned. In all cases, the value of the correlation between local extremes indices and large-scale indices

Table 1. Trend values of winter extreme temperature indices for each zone. *p < 0.05; **p < 0.01

Indices	T_{max90} (°C decade^{-1})	T_{min10} (°C decade^{-1})	F_d (d decade^{-1})	HWD (d decade^{-1})
Zone 1	0.34*	0.1	–2.0	0.7
Zone 2	0.3	0.03	–1	0.7
Zone 3	0.5*	0.4*	–3.0	0.8**
Zone 4	–	0.5*	–	–

Table 2. Correlation matrix between differenced time series of indices of large-scale patterns and extreme temperature event frequencies for each zone and for all regions. NAO: North Atlantic Oscillation; EA: Eastern Atlantic pattern; SCA: Scandinavian pattern; EB: European Blocking pattern; $^{*}p < 0.05$; $^{**}p < 0.01$

	NAO	EA	SCA	EB
$T_{max90\ zone1}$	−0.07	0.41**	−0.15	−0.41**
$T_{max90\ zone2}$	−0.03	0.66**	−0.02	−0.67**
$T_{max90\ zone3}$	0.07	0.52**	−0.05	−0.54**
$T_{max90\ all\ regions}$	−0.004	0.57**	−0.08	−0.58**
$T_{min10\ zone1}$	0.12	0.35*	0.23	−0.30*
$T_{min10\ zone2}$	0.17	0.20	0.37*	−0.20
$T_{min10\ zone3}$	0.26	0.22	0.32*	−0.18
$T_{min10\ zone4}$	0.18	0.17	0.30	−0.18
$T_{min10\ all\ regions}$	0.19	0.17	0.30	−0.18
$F_{d\ zone1}$	0.31*	−0.67**	−0.10	0.54**
$F_{d\ zone2}$	0.15	−0.53**	−0.24	0.48**
$F_{d\ zone3}$	0.10	−0.38*	−0.38*	0.28
$F_{d\ all\ regions}$	0.19	−0.56**	−0.27	0.46**
HWD_{zone1}	0.01	0.04	0.02	0.03
HWD_{zone2}	−0.02	0.33*	0.14	−0.26
HWD_{zone3}	−0.10	0.36*	0.16	−0.39*
$HWD_{all\ regions}$	−0.03	0.27	0.12	−0.22

presents some sensitivity to the zone considered. The degree of this sensitivity varies depending both on the extreme and on the large-scale index in question. In the following, the characteristics of the extremes indices are analysed group by group.

Indices related to the 90th percentile of maximum temperature (T_{max90}) were all significantly correlated with EA and EB. The values of correlation were always greater in the south-eastern zone (Zone 2) and lower in the south-western zone (Zone 1) of the region. Positive EA anomalies and negative EB anomalies can both shift to the south and increase the intensity of the Atlantic jet either over the Atlantic (EA) or over Europe (EB), leading to local weather types characterised by warm and moist westerly or south-westerly wind flowing over the Apennines. This flow is often associated with Apennines föhn episodes, which are more frequent in the eastern part of the region, where the mountains are lower and the wind can easily flow over orography, and is more likely to affect the 90th percentile of T_{max} than other characteristics of this variable. The effects of these events are clearly less pronounced in stations characterised by higher elevation (Zone 1), which are mostly affected by the warm advection itself than by the amplification of it owing to the föhn.

Indices related to the 10th percentile of minimum temperature (T_{min10}) are much less tightly linked to large-scale circulation anomalies as a whole. All the same, in some zones significant values of correlation were observed between this index and the SCA pattern. This is due to the fact that this pattern is linked to the presence of an easterly flow that advects cold air from the Eurasian continent. The eastern part of the region (Zone 2 and 3) is more strongly affected by this circulation pattern than the western part, owing to the presence of a very strong inversion in most parts of the Po valley in winter during night-time. Such inversion makes it very difficult for the cold air coming from the east to penetrate inland. In addition, the EA and EB had a barely significant impact on T_{min10} over the Apennines (Zone 1), the only zone of the domain that is most probably not affected by temperature inversions at the night and can be influenced by warm westerly or south-westerly flow advection.

The F_d index is much more strongly affected by large-scale circulation anomalies than T_{min10}, even though increases in T_{min10} are always associated with decreases in F_d. The warm advection associated with positive EA and negative EB anomalies has a much greater impact on the Apennines (Zone 1 and 2) than on the plains, due to surface inversion during winter nights, while the cold easterly advection correlated with positive SCA anomalies has only a moderate impact on the lower plains. The different sensitivity of T_{min10} and F_d to large-scale circulation indices is an indicator that the general characteristics of the winter T_{min} distribution are much more affected by interannual variability of large-scale flow anomalies than its extremes are.

Finally, the characteristics of HWD are strongly dependent on the altitude of the station considered. This is clearly indicated by the strong changes in sensitivity of this index depending on station elevation (see Fig. 7d with the Zone definition for this index). The most striking characteristic of this index is that sensitivity to the large-scale anomalies decreases substantially from the plains to the higher elevation stations. This result is not a consequence of the low sensitivity of the winter heat waves to variability of large-scale flow anomalies, but rather of the fact that the chosen index may not properly describe the variability in frequency of these events in our region. In particular, the intraseasonal variability of T_{max} at high elevation stations during winter was much lower than the long time-scale variability, or than the trends in Tmax at these locations; at the same time, and as noted previously, decadal trends in mean T_{max} are weaker than those in the frequency of its extremes (T_{max90}), so that during the first part of the period (and for many consecutive years) no heat wave was detected by the index. This leads to problems in identifying the correct relationship between heat waves and large-scale circulation variability, and also to an underestimation of the actual decadal trend in the frequency of these events in winter.

5. CONCLUSIONS

The analysis presented in this study indicates that in Emilia-Romagna during the period 1958–2000, changes in mean minimum and maximum temperature were accompanied by changes in frequency of temperature extreme events. In particular, seasonal minimum and maximum temperatures showed positive trends, the increase being more pronounced in maximum temperature than in minimum temperature. Observed changes in seasonal maximum and minimum temperature and in the frequency of temperature extremes can be summarised as follows:

The 10th and 90th percentile of minimum and maximum temperature for winter, spring and summer have increased

The increases in extreme maximum temperature are more significant than those in extreme minimum temperature

In general, the distribution of annual values of these indices are influenced by summer values

These changes are accompanied by a reduction in the number of frost days (F_d) and by an increase in the heat wave duration (HWD) index

The interannual variability of winter extreme temperature indices was shown to be connected to changes in variability of winter large-scale circulation patterns. The EB and EA patterns have a great influence on the T_{max90} and F_d indices, whereas the SCA pattern influences the variability of T_{min10}. The interannual variability of NAO has only a very moderate link to winter extreme temperature event frequency.

Acknowledgements. We thank Ing. Michele di Lorenzo of ARPA-SMR for kindly helping with the collection of data. This study was conducted within the framework of the project 'Ecosistemi Marini' (SINAPSI) funded by the Consiglio Nazionale delle Ricerche, Ministero della Istruzione Università e Ricerca (CNR-MIUR). This study was also supported by the European Commission as part of STARDEX (STAtistical and Regional dynamical Downscaling of EXtremes for European regions), contract No. EVK2-CT-2001-00115. We thank anonymous reviewers for their helpful suggestions.

LITERATURE CITED

Alexandersson H, Moberg A (1997a) Homogenization of Swedish temperature data. Part I: a homogeneity test for linear trends. Int J Climatol 17:25–34

Alexandersson H, Moberg A (1997b) Homogenization of Swedish temperature data. Part II: homogenized gridded air temperature compared with a subset of global gridded air temperature since 1861. Int J Climatol 17:35–54

Barnston AG, Livezey RE (1987) Classification seasonality and persistence of low-frequency atmospheric circulation patterns. Mon Weather Rev 115:1083–1126

Brazdil R, Budikovà M, Auer I, Böhm R and 9 others (1996) Trends of maximum and minimum daily temperatures in central and southeastern Europe. Int J Climatol 16: 765–782

Brunetti M, Colacino M, Maugeri M, Nanni T (2001) Trends in the daily intensity of precipitation in Italy from 1951 to 1996. Int J Climatol 21:299–316

Cacciamani C, Nanni S, Tibaldi S (1994) Mesoclimatology of winter temperature and precipitation in the Po Valley of Northern Italy. Int J Climatol 14:777–814

Domonkos P, Kysely J, Piotrowicz K, Petrovic P, Likso T (2003) Variability of extreme temperature events in south-central Europe during the 20th century and its relationship with large-scale circulation. Int J Climatol 23:987–1010

Frich P, Alexander LV, Della-Marta P, Gleason B, Haylock M, Klein Tank MA, Peterson T (2002) Observed coherent changes in climatic extremes during the second half of the twentieth century. Clim Res 19:193–212

Galliani G, Filippini F (1985) Climatic clusters in a small area. J Climatol 5:487–501

Houghton JT, Meira Filho LG, Callender BA, Harris N, Kattenberg A, Maskell K (1996) Climate change 1995. The science of climate change. Contribution of Working Group I to the second assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Pavan V, Molteni F, Branković C (2000a) Wintertime variability in the Euro-Atlantic region in observations and in ECMWF seasonal ensemble experiments. Q J R Meteorol Soc 126:2143–2173

Pavan V, Tibaldi S, Branković C (2000b) Seasonal prediction of blocking frequency: results from winter ensemble experiments. Q J R Meteorol Soc 126:2125–2142

Pavan V, Tomozeiu R, Selvini A, Marchesi S, Marsigli C (2003) Controllo di qualità dei dati giornalieri di temperatura minima e massima e di precipitazione. Quaderno Tec ARPA-SIM 15

Press WH, Teukolsky SA, Vetterlinng TW, Flannery BP (1986) Numerical recipes in Fortran: the art of scientific computing, 2nd edn. Cambridge University Press, Cambridge

Wallace JM, Gutzler DS (1981) Teleconnections in the geopotential height field during the Northern Hemisphere winter. Mon Weather Rev 109:784–812

Wijngaard JB, Klein Tank AMG, Konnen GP (2003) Homogeneity of 20th century European daily temperature and precipitation series. Int J Climatol 23:679–692

Wilks SD (1995) Statistical Methods in the Atmospheric Sciences. Academic Press, San Diego, CA

Zuccherelli A (1999–2000) Tesi di laurea: analisi climatica dei dati di temperatura e precipitazione del Nord Italia. Università degli Studi di Bologna, Bologna

Submitted: December 15, 2004; Accepted: December 28, 2005

Proofs received from author(s): June 30, 2006