DETECTION OF VARIATIONS IN AIR TEMPERATURE AT DIFFERENT TIME SCALES DURING THE PERIOD 1889–1998 AT FIRENZE, ITALY

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Abstract. In an attempt to contribute to studies on global climatic change, 110 years of temperature data for Firenze, Italy, were analysed. Means and trends of annual and monthly temperatures (minimum, maximum and average) were analysed at three different time scales: short (20 years), medium (36–38 years) and long (55 years). Comparative changes in extreme events *viz.* frosts in the first and second parts of the 20th century were also analysed. At short time scales, climatic change was found in minimum and average temperatures but not in maximum temperatures. At all three time scales, the annual means of minimum, maximum and average temperatures were significantly warmer in the last part than in the early part of the 20th century. The monthly mean temperatures showed significant warming of winter months. Over the last four decades, minimum, maximum and average temperatures had warmed by 0.4, 0.43 and 0.4 °C per decade, respectively, and if this trend continues, they will be warmer by 4 °C by the end of the 21st century. The significant decline in days with subzero temperatures and frosts in the last half of the 20th century, further substantiated the occurrence of climate change at this site.

1. Introduction

Since the pioneering work of Willet (1950), there has been much interest in the studies of climate change and countless publications on various aspects of climate change in general and on temperature changes or global warming in particular (Mitchell, 1961, 1963; Budyko, 1969, 1977; Stern and Kaufmann, 2000) have been reported. These studies were made on different temporal and spatial scales. Spatial scales ranged from regional (Rupa Kumar and Hingane, 1988; Dessens and Bucher, 1995; Brazdil et al., 1995; Plummer et al., 1995, Razuvaev et al., 1995) to hemispherical (Barnett, 1978; Yamamoto and Hoshiai, 1980; Jones et al., 1982, Stern and Kaufmann, 2000) and to global levels (Jones et al., 1994, 1999; Horton, 1995; Nicholls et al., 1996; Rahmstorf and Ganopolski, 1999). Most of these studies were either based on instrumental data or data simulated through general circulation models (Houghton et al., 1996; Jones et al., 1997). Each of these data sources have their own disadvantages, the former, potentially containing

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observational errors and the later with limitations in accounting for the correct radiative forcings besides inherent down-scaling errors at the regional level. However, for regional scale climatic studies, the instrumental data will have an edge over the simulated data. Further, results obtained from analyses of time series of observed weather data would give useful feedback for correcting physical processes of General Circulation Models, which should lead to better simulations of future climatic scenarios.

For agroclimatologists in particular, study of the impact of climatic changes on agriculture is of foremost importance. Wilson and Mitchell (1987) and Mearns (2000) emphasised the need for information both on smaller regional scales and on variability at shorter time scales for impact studies. Intergovernmental Panel on Climate Change (IPCC) in its reports for the year 1995 and 2002 also highlighted the need to understand regional patterns of climate change. Another important component of climate change, the detection of extreme weather events, is not widely reported, partly due to lack of availability of long-term daily weather data. Changes in both the climatic mean and variability can influence the frequency of extreme events (Mearns et al., 1984; Heino et al., 1999). Changes in climatic variability were reported to have a greater influence on the frequency of climatic extremes than changes in climatic means (Katz and Brown, 1992). Mearns (2000) also reported the importance of understanding the change in climatic variability on various time scales.

In this paper, we examine the long-term climatic change as well as short-term climatic variability of annual and monthly air temperatures at a single site in Italy. We also examined differences in the frequency of extreme temperature events between first and second halves of the study period (1889–1998).

2. Data and Analysis

Figure 1 shows the geographical location of Firenze whose time series of temperature (maximum and minimum) are analysed in this article. Its latitude, longitude and elevations are 43°46′26″N, 11°15′18″E and 74.41 m above m.s.l., respectively. It is located to the southwest of the Apennine mountain range in the central part of Italy. The time series weather data comprises of daily maximum and minimum temperatures and rainfall of 110 years spanning from 1889 to 1998. However, only maximum and minimum temperature data were analysed and reported in this article.

2.1. HISTORY OF THE METEOROLOGICAL STATION

The meteorological observatory of Firenze is at Ximeniano in the centre of the city. The observatory is established on the terrace of a building. This observatory

Figure 1. Geographical location of Firenze, Italy.

was shifted from another location to here as per the recommendations of WMO, Geneva in 1948. The daily observation timings of 9, 15 and 21 h during the period 1879–1941 were changed to 8, 14, and 19 h during 1941–1998.

2.2. HOMOGENEITY TEST

Standard normal homogeneity tests (Alexandersson, 1986; Alexandersson and Moberg, 1997) were performed on maximum and minimum temperature series of all 12 months to detect inhomogeneities in the form of single or multiple shifts in the data. Time series maximum and minimum temperature data of Peretola, a rural station 6 km away from the centre of Firenze has been selected as reference series for conducting this test. The procedure followed for conducting Standard Normal Homogeneity Test (SNHT) explained in Alexandersson and Moberg (1997) is elaborated as follows. After selecting the reference series, the time series of differences between the candidate series and the reference series is calculated. The series containing the differences between candidate and reference series is named the Q-series. The SNHT for single shifts and trends are applied to the Q-series. The null hypothesis is that the Q-series has a constant mean level, i.e. that the candidate series is homogeneous. The alternative hypothesis is that the mean level of Q-series changes abruptly from one level, q_1, to another level q_2 at some point of time, a. In other words, the temperature level of candidate series changes abruptly with the value $q_2 - q_1$ in relation to the reference series at time point a. A test value, T_a^S is calculated for each point of time. The sequence of T_a^S-values is denoted the T-series. The point of time giving the highest value,T_{max}^S is the most likely break point; T_{max}^S is the test static. If T_{max}^S is larger than a predefined critical level (commonly used 95%), then the null hypothesis is rejected. Closer observation of the T-series of both maximum and minimum temperature of all the 12 months showed non-homogeneous values of more than 10 years in the monthly minimum temperature series of January (1963–1974) and August (1977–1990) and in the monthly maximum temperature series of August (1977–1990). These inhomogeneities might have been caused by any of the four factors identified by Mitchell (1953) *viz.* (1) changes in instrumentation, exposure and measurement techniques, (2) changes in station location, (3) changes in observation times and methods used to calculate monthly means, and (4) changes in the environment around the station, particularly with respect to urban growth.

Evidence for these inhomogeneities is partially found in the history of the meteorological observatory. Though shift in location and changes in observation timings were made in 1940s, inhomogeneities appeared in late 1970s. So, the factors 1–3 (cited in the previous paragraph) may not be responsible for the inhomogeneities noticed in the data series. But, the fourth factor, i.e., urban growth appears to be partly responsible for inhomogeneities, as the inhomogeneities are neither continuing up to the recent year nor are appearing in all the months. In view of the presence of negligible amount of non-homogeneous observations in a longer series of 110 years, no corrections were made in temperature series.

2.3. URBANISATION EFFECT

The effect of urbanisation on the temperature data of Firenze was studied by comparing the mean annual minimum, maximum and average temperature (half the sum of maximum and minimum) of Firenze with the corresponding data of a rural station, Peretola. In this analysis, temperature data of both urban and rural sites for 48 years (1951–1998) were compared. Trends of minimum, maximum and average temperature in urban and rural sites were also compared (Figure 2).

Commonly noticed and widely reported (Colacino and Rovelli, 1983; Karl et al., 1988) urbanisation effects like significant rise in minimum than in maximum temperatures and narrowing down of diurnal temperature range are noticed in this study also. It is interesting to note that rate of increase of minimum temperature is 20 times higher and rate of increase of maximum temperature is half times lesser in urban area compared to the rural site. However, average temperature is not at all affected by urbanisation and its rate of increase remains the same in both urban and rural sites. As urbanisation effect is felt in only minimum temperatures of past

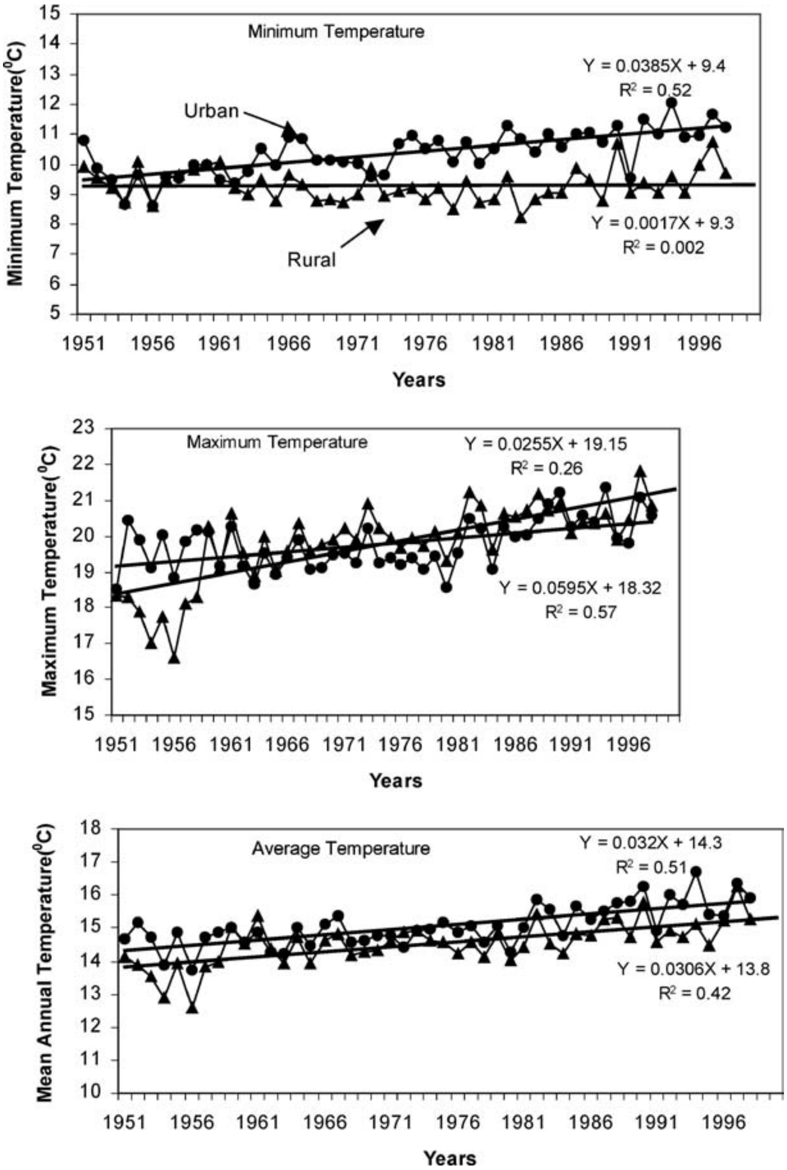

Figure 2. Mean annual minimum, maximum and average temperature trends at urban and rural sites.

30 years (evidenced from the figure), attempt was not made for its correction at this stage.

The population data of Ximeniano area, where the observatory of Firenze is located, and the population data of rural station Peretola (presented later) shows that Ximeniano registered negative growth of population over 20th century whereas Peretola registered no significant population growth (though positive).

Population growth at Ximeniano (Urban) and Peretola (Rural)

Year	Ximeniano area	Peretola Area
1911	20211	
1921	21091	8429
1931	20461	9917
1936	19706	10174
1951	18607	10894
1961	13868	11747
1971	9610	12205
1981	8920	12192
1991	5976	12314
2001	4004	12437

The urbanization effect on temperature series of Firenze cannot be corrected as a function of population growth (Karl et al., 1988) as the temperature series of Firenze showing higher temperature over the rural station, has negative population growth compared to that of the rural station. Other factors like canyon geometry or air pollution may have contributed for the higher minimum temperature in urban area than in rural site. But, correction for their effect on temperature cannot be attempted due to lack of data on these parameters.

2.4. AUTO-CORRELATION

An important guide to the properties of time series is provided by auto-correlation coefficients at different lags. Auto correlation was performed separately on the time series of annual minimum, maximum and average temperature values. The auto-correlations at different lags with respect to minimum temperature or maximum temperature or average temperature showed auto-correlation coefficient (r_k) of fairly larger values at shorter lags and nearly zero values at longer lags, which is a characteristic of time series with short-term correlations. The auto-correlations at different lags did not indicate any seasonality, randomness and non-stationary patterns in the total time series.

Moreover, annual temperatures, i.e. minimum, maximum and average temperature series showed higher and positive auto-correlations of values 0.63, 0.38 and 0.50, respectively at lag-1, thus indicating greater persistence and non-randomness in the data series.

2.5. TESTS OF RANDOMNESS

Some tests of randomness like serial correlation coefficient (r1) and Von Neumann ratio (v) tests recommended by WMO (1966) were applied on the total time series of annual minimum and maximum temperature. The r1 and v values obtained for minimum temperature are 0.66 and 0.68, respectively, and comparison of them with critical values rejects the null hypothesis of randomness. It is also the case with maximum temperature series, with sampled r1 and v values of 0.42 and 1.12, respectively.

2.6. ANNUAL MEANS

Annual mean maximum and minimum temperatures were calculated by averaging the temperatures over 365 days of each year. Thus, time series of both maximum and minimum temperatures for 110 years were generated.

2.7. MONTHLY MEANS

Monthly means of maximum or minimum temperatures of each month in each year of the series were worked out by averaging over the days of that month in that year. Thus, time series monthly mean maximum and minimum temperatures of 110 years for each of the calendar months of a year (110 $\times$ 12) were generated.

3. Results and Discussion

The 110-year time series of minimum, maximum and average temperatures along with their 10-year Gaussian filters are presented in Figure 3. The minimum temperature series shows three distinct periods of change in minimum temperature *viz*., the period from 1889 to 1924 showing cooling trend, period from 1925 to 1960 showing no trend and 1961 to 1998 showing increasing trend. The maximum temperature showed alternate peaks and troughs at short intervals (10–20 years) until 1960s followed by increasing trend afterwards. The average temperature also showed alternate peaks and troughs until 1960s followed by slow increase in average temperatures.

The three periods showing different patterns of change in minimum temperature makes it necessary to analyse the minimum temperature series in the three periods mentioned earlier of 36–38 years (i.e. medium time scale). To maintain uniformity of analysis with other two series, the analysis at medium scale (36–38 years) has been extended to the time series of maximum and average temperatures also. Moreover, all these three time series are showing increasing trend from 1960s onwards and most of the studies on climatic change or global warming also reported strong warming trend since 1961 (Yan et al., 2002). As maximum and average temperature series are showing alternate peaks and troughs at smaller intervals, attempt was made to study variations in the time series of minimum, maximum and average temperatures at shorter time scale of 20 years. To complete the analysis at all the three time scales, namely, short, medium and long time scales, the

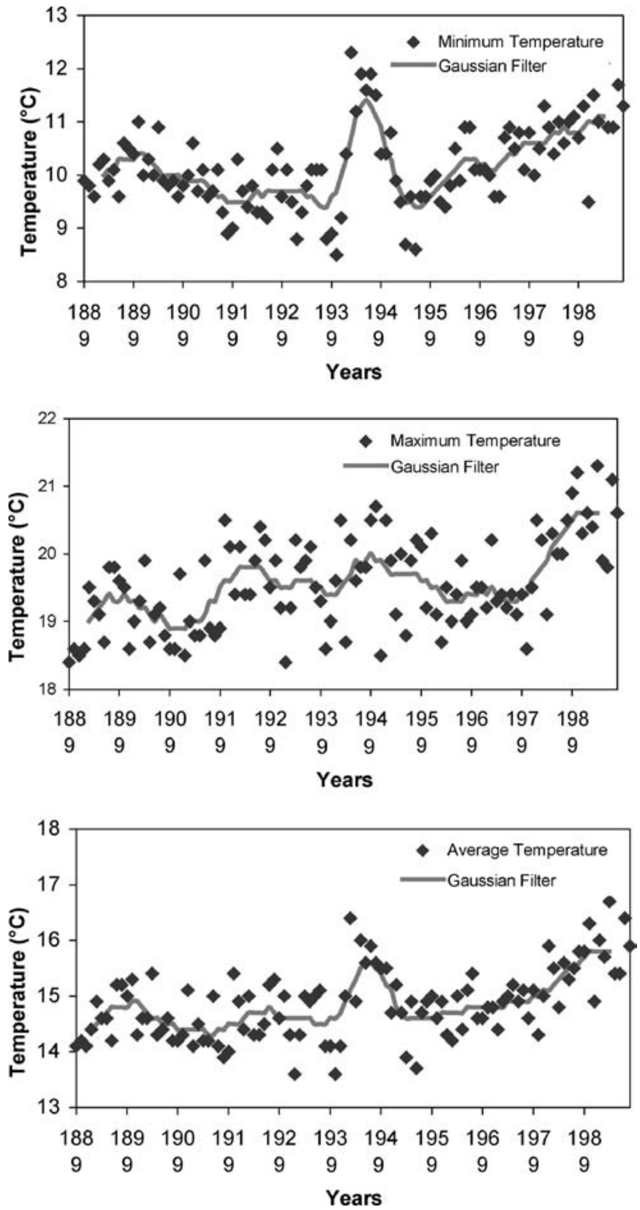

Figure 3. Time series of annual minimum, maximum and average temperatures (along with 10-year Gaussian filters) at Firenze.

pattern of minimum, maximum and average temperatures at long time scale of 55 years during the periods 1889–1943 and 1944–1998 was also analysed. It is also mentioned in Chatfield (1980) that it is a good idea to split a time series of reasonable length into two or more segments and to compare the properties of each segment.

The total study period of 110 years (1889–1998) is treated as a century and this period is referred as last century or 20th century in this article. In short time scale, the 110 years data series (1889–1998) has been divided into five 20-year periods and a 10-year period. Similarly, periods from 1889 to 1924, 1925 to 1960 and 1961 to 1998 were referred as first, second and third one-third parts of the century, in the medium time scale. Likewise, the 110 years series is divided into two halves and the periods 1889–1943 and 1944–1998 are referred as first and second halves of the century, in the long time scale.

Detailed analysis of both the annual and monthly temperature series of 110 years over three time scales *viz.*, (1) short time scale (20 years averaging period); (2) medium time scale (36–38 years); and (3) long time scale (55 years) is presented as later.

3.1. ANNUAL MEANS OF MAXIMUM AND MINIMUM TEMPERATURES

3.1.1. *(a) Short Time Scale (20 years)*

The annual mean minimum, maximum, average temperatures and diurnal temperature range averaged over each 20 years period, starting from 1889 is presented in Table I. Though the mean minimum temperature over 20 years time scale are showing alternative increasing and decreasing trends in successive 20-year periods up to late 1960s, the decrease in minimum temperature up to late 1920s only was significant. From the early 1970s onwards mean minimum temperature maintained a steady and significant increasing trend. This is making true the foresighted observation of Hansen et al. (1981) that the anthropogenic carbon dioxide warming should emerge from the noise level of natural climatic variability by the end of

TABLE I
Annual mean minimum, maximum and average temperatures in °C (short time scale)

Period	Min. Temp*	Max. Temp*	Avg. Temp*	DTR**
1889–1908	10.1	19.1	14.6	9.0
1909–1928	9.7 (2.9, <0.00)↑	19.4 (1.6, 0.06)	14.5 (0.44, 0.33)	9.7 (4.5, <0.00)
1929–1948	10.2 (1.6, 0.06)	19.5 (0.8, 0.21)	14.9 (1.5, 0.07)	9.4 (1.2, 0.12)
1949–1968	9.9 (0.89, 0.19)	19.6 (0.38, 0.35)	14.8 (0.46, 0.32)	9.7 (1.2, 0.12)
1969–1988	10.5 (3.3, <0.00)	19.6 (0.09, 0.46)	15.0 (1.9, 0.03)	9.1 (2.7, <0.00)
1989–1998	11.1 (2.4, 0.01)	20.6 (5.0, <0.00)	15.8 (4.1, <0.00)	9.5 (2.0, 0.03)
1889–1998	10.2	19.6	14.9	9.4

*Min. Temp, Max. Temp and Avg. Temp refer to minimum, maximum and average temperatures respectively.
**DTR: diurnal temperature range.
↑Values in the parenthesis are t-values and P-levels to test the significance of the difference between means of a period and its previous period.

the 20th century. These types of fluctuations in time series of average temperatures were reported earlier too (Muller et al., 1995). The increasing trend in the mean minimum temperatures after 1960s and 1970s of the 20th century at both regional and global levels reported earlier (Brazdil et al., 1995; Ye et al., 1995; Torok and Nicholls, 1996) is similar to this observation.

Unlike the minimum temperature, the maximum temperature is not showing any fluctuations and the 20-year mean maximum temperature is maintaining an insignificant but steady increasing trend up to seventies. The last 10-year period (1989–1998), however witnessed a highly significant increasing trend. Many of the studies reported higher increase in minimum temperature than in the maximum temperature and some (for instance, Dessens and Bucher, 1995) even reported decrease in maximum temperature in the 20th century.

Average daily temperatures (average of maximum and minimum) and diurnal temperature range (difference between maximum and minimum) also showed fluctuations in their 20-year means, similar to the observations made for east Mediterranean region (Repapis and Philandras, 1988). However, the increase in average temperature is significant after 1970s only. The highest maximum, minimum and mean temperatures for the last 110 years of the study period were recorded in the last 10-year period of the data series (1989–1998) similar to the global-level observations (http://www.wmo.ch).

3.1.2. *(b) Medium Time Scale (36–38 years)*

The mean annual minimum, maximum and average temperatures as well as diurnal temperature ranges calculated over 36-, 36- and 38-year period (Table II) show that the increase in minimum temperatures was insignificant in the second one-third part of the century compared to the first part and reverse is true in case of maximum temperatures. However, it is strange to note that the maximum and minimum temperatures are reversing their trends in last or the third part of the century and the increase in mean minimum temperature of the third part over its mean in the second part is highly significant and reverse is the case for maximum temperature. This is in agreement with the results reported by Karl et al. (1993),

TABLE II

Annual mean minimum, maximum and average temperatures (medium time scale)

Period	Minimum temperature	Maximum temperature	Average temperature	DTR
1889–1924	9.9	19.2	14.5	9.2
1925–1960	10.0 (0.31, 0.38)*	19.7 (3.7, <0.00)	14.8 (2.1, 0.02)	9.7 (2.5, 0.01)
1961–1998	10.6 (3.0, <0.00)	19.8 (1.0, 0.17)	15.2 (2.5, 0.01)	9.2 (2.4, 0.01)

*Values in the parenthesis are t-values and P-levels to test the significance of the difference between means of a period and its previous period.

that during 1951–1990, over 37% of global land mass, minimum temperatures were warmed by 0.84 °C compared to only 0.28 °C for maximum temperatures. The daily average temperatures (annual means) were maintaining significant increasing trend and the mean annual temperature of each one-third part of the study period is warmer over its previous part by 0.3–0.4 °C. It is in agreement with the trends observed over the global land mass (Jones, 1995; Baker et al., 1995) i.e. of an increase of air temperature by 0.33 °C. The mean diurnal temperature range (DTR) is not the least in the last one-third part (1961–1998) of century but significantly lesser by 0.5 °C compared to its previous part (1925–1960). Diurnal temperature range being the same in first and last periods, no trend in DTR over the century was noticed. It is contradicting the observations in Australia (Plummer et al., 1995), Ireland, Italy, Thailand, Turkey and Bangladesh (Jones, 1995), Cyprus (Price et al., 1999) and over larger areas of the globe (Horton, 1995), where decreasing trend in DTR was noticed over the last century.

3.1.3. *(c) Long Time Scale (55 years)*

The annual means of both maximum and minimum temperatures of the last half (1944–1998) of the study period is showing highly significant increasing trend over its first half (1889–1943). Mean annual minimum temperature of the last half is higher by 0.6 °C than the mean of the first half (Table III).

Mean annual maximum temperature is also showing a similar trend and the mean maximum temperature of the second half of the century is higher by 0.5 °C compared to the mean maximum temperature of the first half of the century. The increases in annual maximum and minimum temperatures of the second half century by 0.5° and 0.6 °C, respectively, over those in the first half partially confirm the observation made by Price et al. (1999), as the increase in minimum temperature is marginally higher than the maximum temperature.

Mean annual average temperature is also significantly higher in the second half of the century than in first half. However, the difference in diurnal temperature range between the two halves is not statistically significant.

TABLE III
Annual mean minimum, maximum and average temperatures (long time scale)

Period	Minimum temperature	Maximum temperature	Average temperature	DTR
1889–1943	9.9	19.3	14.6	9.5
1944–1998	10.5	19.8	15.1	9.3
1889–1998	10.2	19.6	14.9	9.4
t-value[a]	4.7	3.9	5.1	1.16
P-level[a]	<0.00	<0.00	<0.00	0.12

[a] t-values and P-levels to test the significance of the difference between means of periods 1889–1943 and 1944–1998.

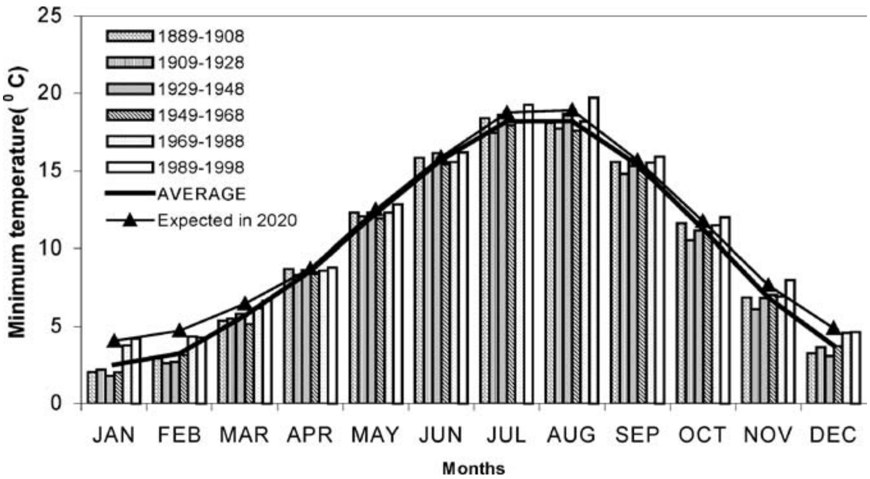

Figure 4. Monthly mean minimum temperature in different double decades of the last century.

3.2. MONTHLY MEANS OF MAXIMUM AND MINIMUM TEMPERATURES

3.2.1. *(a) Short (20 years) Time Scale*

The mean monthly minimum temperatures of all the calendar months in the last part of the 20th century (1989–1998) were higher compared to the minimum temperatures of all the months in the period 1889–1908, exactly 100 years back (Figure 4). However, the increase in minimum temperature in the last part of the 20th century over the early parts of the century is higher in the winter months, i.e. December, January and February. The warming of winters over most parts of the globe is well referenced (Brazdil et al., 1995; Razuvaev et al., 1995; Yan et al., 2002). The probable minimum temperatures in each of the 12 calendar months in the year 2020, worked out by using linear trend analysis of the whole time series data (referred as trend) are higher compared to the long term averages of the respective months. The differences between the long-term averages and trends in 2020 are also more apparent in winter months.

Like the minimum temperature, the mean monthly maximum temperatures of the last part of the 20th century (1989–1998) were higher than their counter parts exactly 100 years back in the period 1889–1908 (Figure 5). Interesting pattern observed in the monthly means of maximum temperature of different 20-year period is that the increase in maximum temperature in the last 10-year period (1989–1998) over the early parts of the century is more significant in the months of January, February and March and also in summer months like June, July and August. In rest of the months the increase in temperature is not much.. The months from January to August, in the past 100 years, registered highest monthly means of maximum temperature in the last 10-year period (1989–1998) of the 20th century.

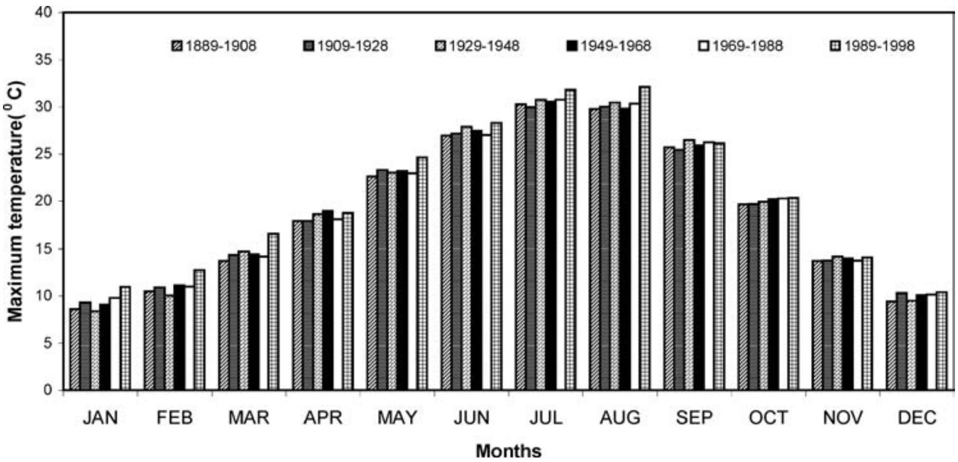

Figure 5. Monthly mean maximum temperatures in different double decades of the last century.

3.2.2. *(b) Medium Time Scale (36–38 years)*

The monthly mean minimum temperatures in later part (1961–1998) of the century in all the months are comparatively higher than the minimum temperature means of the respective months in the early parts of the century, i.e. 1889–1924 (Table IV). However, the relative increase is more conspicuous and significant in months from October to March and also in August and is insignificant in other months. Increase in mean minimum temperature by more than 1 °C is observed in January and February. These observations confirm the findings made elsewhere at both regional and global levels that the minimum temperatures are increasing more in winter (Karl et al., 1996; Karl and Easterling, 1999; Plummer et al., 1999; Zhai et al., 1999). In the middle part of the century (1925–1960), no significant increase in minimum temperatures compared to the early part (1889–1924) was noticed in any of the months. The higher jump in minimum temperatures over its previous part, in months October–March, was also noticed in the last part of the century (1961–1998). Most of the studies on global warming and temperature changes reported the spurt in the increasing trend of minimum temperatures after 1960s only (Jones et al., 1994; Plummer et al., 1999; Zhai et al., 1999; Yan et al., 2002).

The monthly mean maximum temperatures in months January, February, March, April, July, August and October of the last part of the century (1961–1998) are significantly higher over the respective months in the early part, i.e. 1889–1924 (Table V). However, the increase in mean maximum temperatures of most of the months (except January, February, March and December) in middle part of the century over the early part was more significant than the increase in last part over the middle. Not only the nights (minimum temperatures) but also the days (maximum temperatures) of main winter months January and February were significantly warmer in the last part of the century compared to its previous part.

TABLE IV

Monthly mean minimum temperatures (°C) of 12 calendar months (at medium time scale)

Period	January	February	March	April	May	June	July	August	September	October	November	December
1889–1924 (1)	2.1	2.7	5.4	8.5	12.3	15.5	17.9	18.0	15.2	11.1	6.4	3.5
1925–1960 (2)	2.0	2.8	5.4	8.4	12.1	15.8	18.3	18.2	15.4	10.9	6.7	3.3
1961–1998 (3)	3.5	4.2	6.1	8.7	12.4	15.7	18.4	18.5	15.6	11.7	7.4	4.3
Student's t-test values for testing the significance of differences in means between two subperiods												
1 and 2	0.35	0.32	0.01	0.36	0.78	0.88	1.17	0.68	0.59	0.61	1.04	0.46
	(0.37)	(0.37)	(0.50)	(0.36)	(0.22)	(0.19)	(0.12)	(0.25)	(0.28)	(0.27)	(0.15)	(0.32)
2 and 3	3.32	2.83	1.82	1.09	0.89	0.26	0.14	0.85	0.41	2.16	2.08	2.56
	(<0.00)	(<0.00)	(0.04)	(0.14)	(0.19)	(0.40)	(0.44)	(0.20)	(0.34)	(0.02)	(0.02)	(0.01)
1 and 3	3.25	3.59	2.17	0.85	0.21	0.75	1.51	1.86	1.22	1.69	2.81	2.28
	(<0.00)	(<0.00)	(0.02)	(0.20)	(0.42)	(0.23)	(0.07)	(0.03)	(0.11)	(0.05)	(<0.00)	(0.01)

TABLE V
Monthly mean maximum temperatures (°C) of 12 calendar months (at medium time scale)

Period	January	February	March	April	May	June	July	August	September	October	November	December
1889–1924 (1)	8.8	10.5	14.1	17.8	23.0	26.9	30.1	29.7	25.5	19.5	13.5	9.9
1925–1960 (2)	9.0	10.6	14.5	18.7	23.1	27.8	30.8	30.4	26.3	20.1	14.2	9.9
1961–1998 (3)	9.8	11.5	14.8	18.5	23.4	27.3	30.9	30.6	26.1	20.4	14.0	10.0
Student's t-test values for testing the significance of the differences in means between two subperiods												
1 and 2	0.43	0.2	1.2	2.7	0.16	2.4	1.9	2.1	2.0	1.6	2.2	0.04
	(0.34)	(0.4)	(0.12)	(0.01)	(0.44)	(<0.00)	(0.03)	(0.02)	(0.03)	(0.05)	(0.01)	(0.48)
2 and 3	1.9	1.6	0.69	0.78	0.75	1.39	0.39	0.5	0.61	0.95	0.74	0.4
	(0.03)	(0.05)	(0.25)	(0.22)	(0.23)	(0.08)	(0.35)	(0.31)	(0.27)	(0.17)	(0.23)	(0.35)
1 and 3	2.5	2.4	1.8	2.2	0.90	1.12	2.5	2.1	1.3	2.4	1.4	0.4
	(0.01)	(0.01)	(0.04)	(0.02)	(0.18)	(0.13)	(0.01)	(0.02)	(0.1)	(0.01)	(0.08)	(0.36)

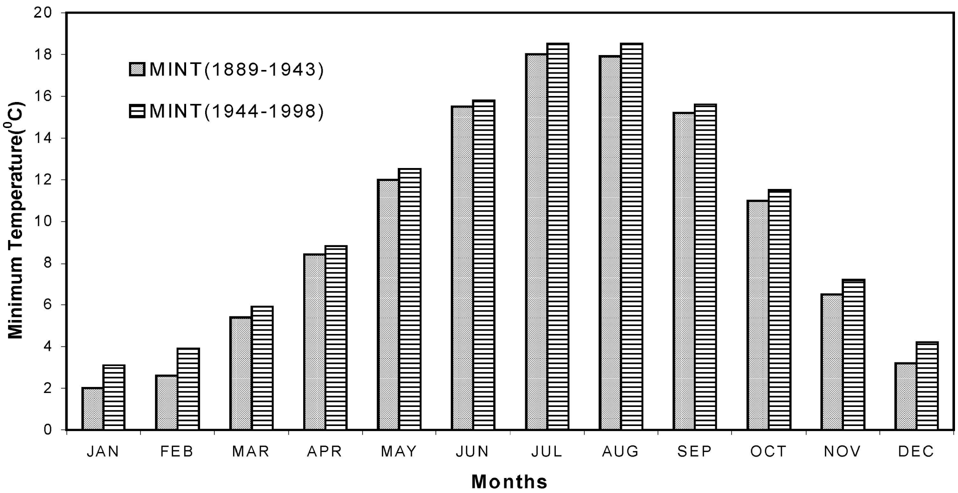

Figure 6. Monthly mean minimum temperature during first and second halves of the last century.

3.2.3. *(c) Long Time Scale (55 years)*

The monthly mean minimum temperature of all the 12 calendar months except June and September of the second half of the century (1944–1998) are significantly (at 5% probability) higher than the mean minimum temperatures of the early half of the century (1889–1943). However, the increase in the mean monthly minimum temperature of the last half of the century over the means of previous half century is more conspicuous and highly significant ($P < 0.001$) in the winter months (December, January and February) than in other months (Figure 6). Similar observation of warm winter nights was noticed towards last one-third of the 20th century in the previous section on medium time scale analysis of minimum temperatures also. These observations are part of the large-scale warming of winter nights taking place not only over northern hemisphere but also over the entire globe (Razuvaev et al., 1995; Torok and Nicholls, 1996; Heino et al., 1999; Plummer et al., 1999; Yan et al., 2002).

The mean maximum temperatures in all the months (except November) of the second half of the century are higher over the means of their counter parts in the early half. However, the increase is statistically significant in the months of January, February, April, May and July only (Figure 7).

3.3. TRENDS OF ANNUAL MINIMUM, MAXIMUM AND AVERAGE TEMPERATURES

3.3.1. *Linear Trends Using Simple Regression*

The trends of temperatures at short time scale (20 years) were not worked out because WMO (1966) recommends that where length of records permits, the climatic data should be summarized for a standardized period of years longer than the earlier

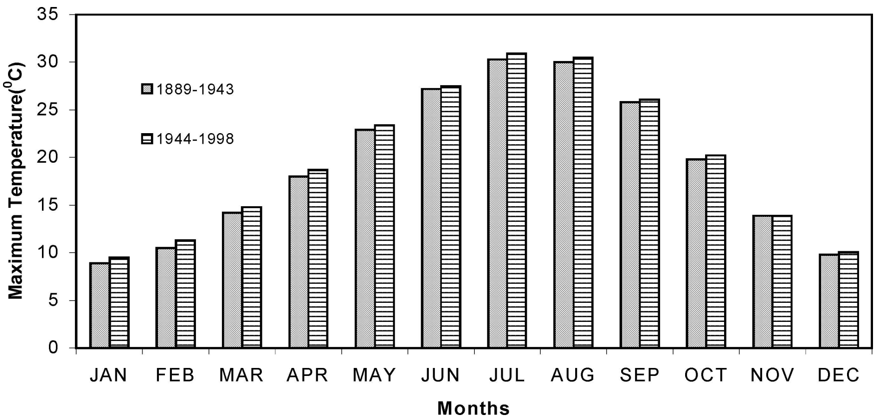

Figure 7. Monthly mean maximum temperature during first and second halves of the last century.

defined 30 years normal. Hence, trends were reported in this article for medium (>36 years) and higher (>50 years) time scales only.

3.3.1.1. *Medium Time Scale.* The trends of annual minimum temperature at medium scale in early, middle and last part of the century are quite interesting to note (Figure 8). While the middle part of the century (1925–1960) remained near normal without significant increasing or decreasing trends, its earlier (1889–1924)

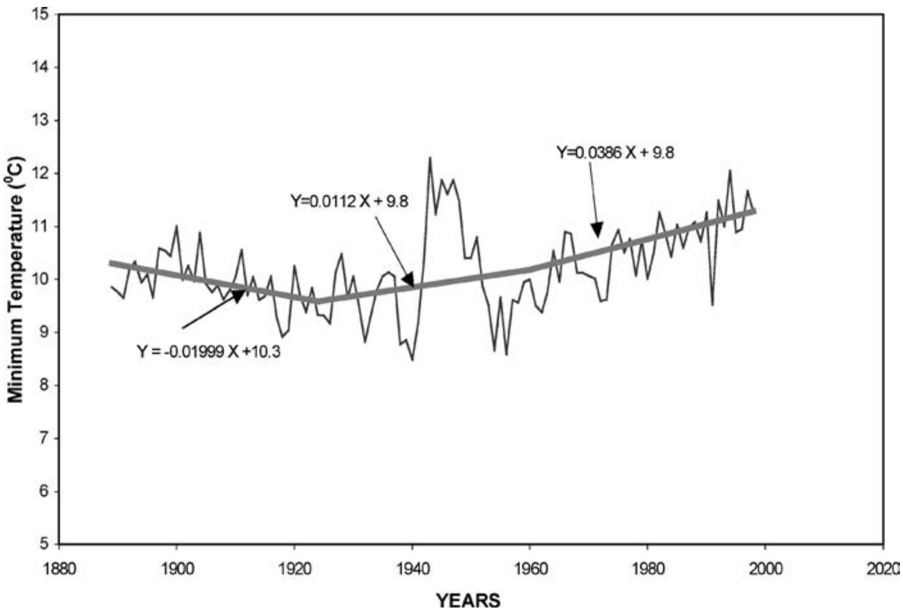

Figure 8. Trends of annual minimum temperature in three different parts of the century (medium scale).

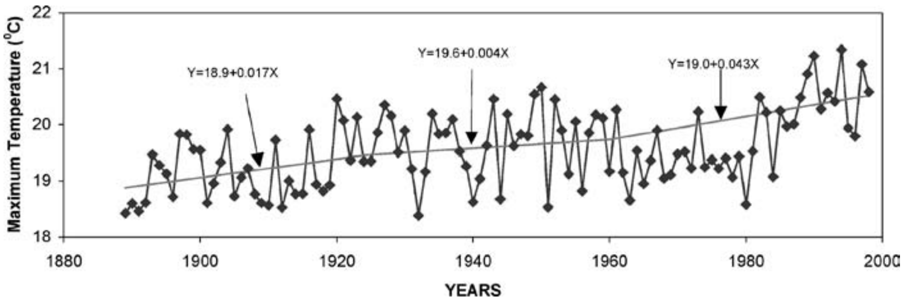

Figure 9. Trends of mean annual maximum temperature during three parts of the 20th century.

and later (1961–1998) parts showed significant decreasing and increasing trends, respectively. The minimum temperatures of the 20th century progressed from a mild cooling trend with decrease of 0.2 °C per decade in the early part through no trend in middle part to an abruptly warming period (increase of 0.4 °C per decade) of the last part of the century. The observation of cooling periods before 1960s and abrupt warming thereafter is synchronous with the trends of the minimum temperatures observed elsewhere.

Except in the earlier part, the trends of maximum temperatures in the other two time periods of the century (Figure 9) were also in line with the trends of minimum temperatures in those two parts (1925–1960 and 1961–1998). However, unlike the minimum temperature, maximum temperature showed an increasing trend in the earlier part of the century. The maximum temperatures maintained a moderate increasing trend in the early period (increase of 0.16 °C per decade) followed by no trend in the middle years and a steep increasing trend of 0.43 °C per decade in the last part of the century. Though these observations agree well with the increasing trends of minimum temperatures elsewhere, they contradict the low or negative trends in maximum temperature compared to minimum temperature, observed in some regions (Karl et al., 1991; Dessens and Bucher, 1995; Karl and Easterling, 1999).

The trends of daily average temperatures (the mean of maximum and minimum) in first and second parts of the century were not significant but the trend in the last part of the century (1961–1998) is highly significant. After the 1960s, the daily average temperature is showing a strong increasing trend with an increase of 0.4 °C per decade (Figure 10). If the temperature continues to rise at this rate, at the end of 21st century, mean annual daily temperature will be warmer by 4 °C. This observation is more alarming as the temperature likely to prevail in this region at the end of 21st century is around the higher limits of expected global temperatures at the end of century based on current emission trends of greenhouse gases (World Resources, 1994).

3.3.1.2. *Long Time Scale (55 years).* All the temperature parameters, i.e. minimum, maximum and average temperatures could establish statistically significant trends

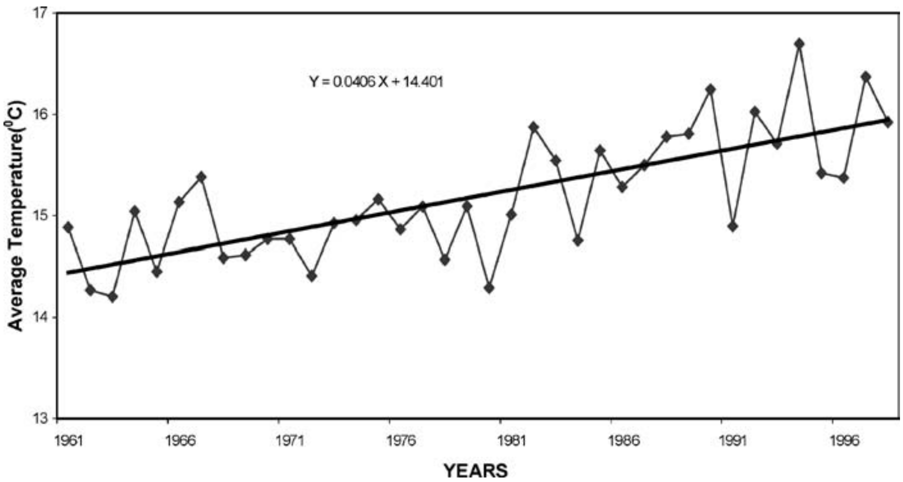

Figure 10. Trends of daily average temperature during 1961–1998 (medium scale).

only in the second half of the century (Table VI). In the first half of century, minimum and maximum temperatures were maintaining opposite trends of cooling and warming, respectively. As a result, average temperature did not show any significant trend in the first half. It was interesting to observe the reversal of trend by minimum temperature in the second half (positive) compared to the first half of century (negative). Though, the rate of increase of average temperature in the first half was insignificant (0.02 °C per decade), it increased by seven to eight times (0.15 °C per decade) in the second half.

3.3.1.3. *Total Time Series.* The total time series is depicting statistically significant trends of increase in minimum, maximum and average temperature during the last century (1889–1998). The rates of increase of maximum and average temperatures (0.1 °C per decade) are slightly higher than the rate of increase of minimum temperature (0.09 °C per decade).

TABLE VI

Trends of (°C per decade) minimum, maximum and average temperatures in first half, second half and the total series of the study period

Parameter	1889–1943	1944–1998	1889–1998
Minimum temperature	−0.10*	0.10*	0.09**
Maximum temperature	0.15**	0.16**	0.10**
Average temperature	0.02	0.15**	0.10**

* and ** indicate significance at 0.05 and 0.01 probability, respectively.

TABLE VII
Mann–Kendall rank statistic and Spearman rank statistic (r_s) for identifying trends in minimum and maximum temperature series

	Mann–Kendall's (t)		Spearman rank statistic (r_s)	
Period	Minimum	Maximum	Minimum	Maximum
1889–1924	−0.30**	0.22	−0.44**	0.33
1925–1960	0.05	0.05	0.10	0.07
1961–1998	0.49**	0.47**	0.68**	0.66**
1889–1443	−0.24**	0.28**	−0.32**	0.41**
1944–1998	0.27**	0.24**	0.32**	0.34**
1889–1998	0.23**	0.31**	0.41**	0.49**

**Significant at 0.01 confidence level.

3.3.2. *Trends Using Non-Parametric Tests*

Besides estimating linear trends using least squares regression technique, presence of trends in different subperiods as well as the whole time series was studied using some simple but powerful tests for identifying trend against randomness like Mann–Kendall rank statistic and the Spearman rank statistics (r_s), recommended by WMO (1966).

The aforementioned two tests were applied to the annual minimum and maximum temperature values of the whole period (1889–1998) and also to different subperiods at medium and longer time scales. The significance of temperature trends (minimum and maximum) during different subperiods and whole period as indicated by the Mann–Kendall rank statistic (τ) and Spearman rank correlation (r_s) values (Table VII) are similar to the significance pattern of the linear trends (using least square regression technique) in different subperiods. These advanced tests specially designed for time series analysis also indicate highly significant increasing trends in both minimum and maximum temperatures over the whole time series, which are similar to the linear trends reported in previous pages. The increasing trends of minimum as well as maximum temperatures were found to be more pronounced and significant during the last four 20-year periods (1961–1998) of the 20th century than in other subperiods.

Further detailed investigation of temperature (minimum and maximum) fluctuations have been carried out by applying Cramer's t_k-statistic test on nine-term running means over the total time series. The Cramer's t_k-statistic test is defined as (WMO, 1966)

$$t_k = \left[n(N-2)\big/\left(N - n\left(1 + A_k^2\right)\right)\right]^{1/2} A_k,$$

in which

$$A_k = (\bar{X}_k - \bar{X})/s, \tag{1}$$

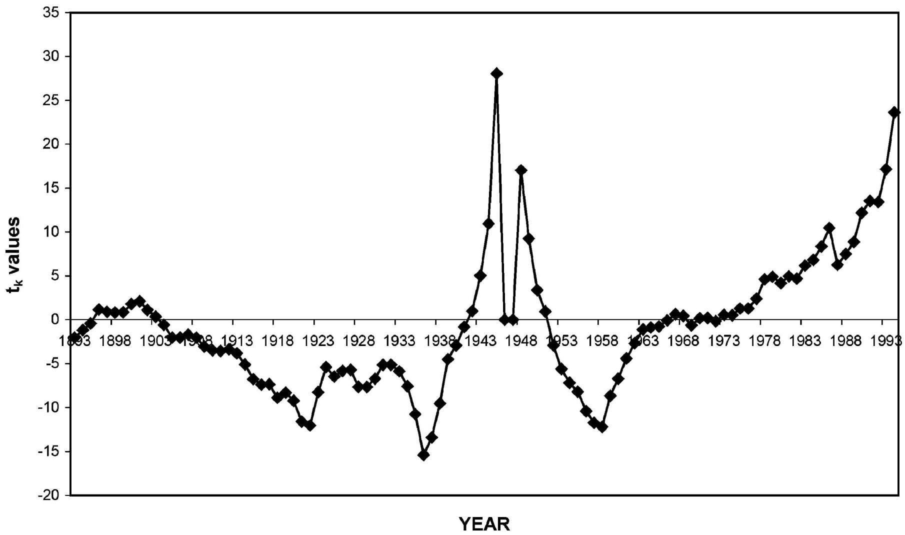

Figure 11. Cramer's t_k statistic test for minimum temperature during 1889–1998.

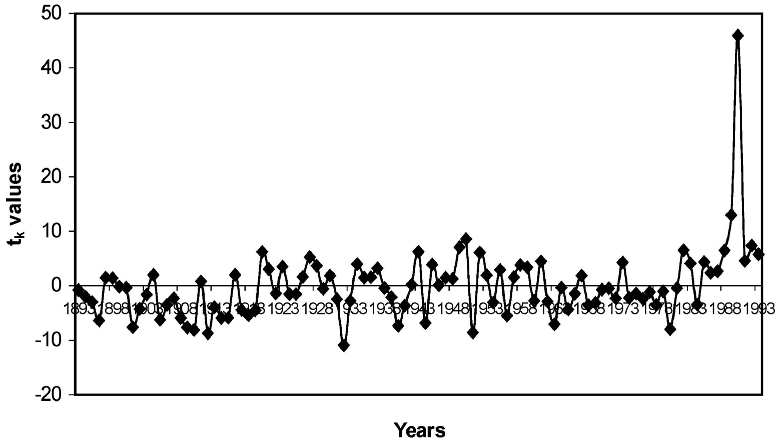

Figure 12. Cramer's t_k statistic test for maximum temperature during 1889–1998.

where $\bar{X}$ and s are the mean and standard deviations, respectively, of the entire series; $\bar{X}_k$ is the k-term running mean; N the number of observations.

The plot of t_k values over the entire time series of annual minimum (Figure 11) and maximum (Figure 12) temperatures showed decreasing trend in minimum temperatures (with intermittent short fluctuations) up to the year 1936. The 9-year mean minimum temperature attained its lowest value centred around 1936 after which a steep increasing trend is observed up to 1945 followed by a sharp declining trend in the next 13 years to reach a second lowest value around the year 1958. Similar peak in surface air temperature around the 1940s was observed over the northern latitudes as well as the entire globe (Hansen et al., 1981). The last four decades from

1958 to 1998 maintained continuous increasing trend. The 9-year mean of maximum temperatures, however, remains stationary (no trend) up to 1980 followed by an increasing trend after 1980s to reach a peak around 1990.

3.4. TEMPERATURE EXTREMES

In the temperate climatic conditions, frosts are the main weather hazards causing substantial losses to agricultural crops and horticultural systems. The changes in extreme weather conditions over a region are good indicators of climatic change also. To understand the climatic change in terms of low-temperature extremes of agricultural importance, different temperature extremes like (1) the number of days with minimum temperature less than 0 °C (partial frost days); (2) maximum temperature less than 0 °C (total frost days); (3) minimum temperature less than −4 °C, etc. were worked out. According to the temperature conditions specified for occurrence of total and partial frosts (Dalezios et al., 2000), the days with daily maximum temperatures less than 0 °C were termed as total frost days and minimum temperatures less than 0 °C were termed as partial frost days.

The details of the extreme events (Table VIII) shows that the number of subzero minimum temperature events per year or, in other words, days with partial frost conditions were substantially (significantly) decreased in the latter half of the century compared to the first half. Similar declining of cold temperatures and cold temperature-related extremes (frosts) in past 40–50 years were noticed in northern and central Europe (Heino et al., 1999), China (Zhai et al., 1999) and Australia and New Zealand (Plummer et al., 1999). However, total frost days or the days with maximum temperature less than 0 °C did not differ significantly. The days with −4 °C in the latter half also declined when compared to first half. It is understood from the analysis that total frost occurs once in 4 years but the partial frosts are occurring frequently in this region. The partial frosts can be further classified as

TABLE VIII
Details of extreme low temperature events per year in two halves of the study period

Period	Average number of days per year (Min. tem. <0 °C)	Average number of days per year (Min. tem. −4 °C)	Average number of days with partial frosts			Average number of days with total frost
			Mil*	Mod*	Sev*	
1889–1998	22.1	2.2	19.9	2.1	0.06	0.4
1889–1943	26.0	2.4	23.6	2.3	0.05	0.4
1944–1998	18.2	2.0	16.2	1.9	0.07	0.4
t-value**	8.97	1.36	9.03	1.45	0.38	0.31
P-level	<0.00	0.09	<0.00	0.07	0.35	0.38

*Mil: mild; Mod: moderate; Sev: severe; Min. Tem: minimum temperature.
**t-values and P-levels to test the significance of the difference between means of periods 1889–1943 and 1944–1998.

mild frosts with minimum temperatures ranging between 0 and −4 °C, moderate frosts with minimum temperatures ranging between −4 and −10 °C and severe frosts when minimum temperatures are below −10 °C. The details show that the numbers of days with mild frosts are more than the days with other two categories in both halves of the century. The occurrence of mild frosts has declined significantly in the latter half of the century than in the first half. The moderate frosts were also noticed to be declining(at 7% probability) in the second half, but the severe frosts did not show any significant change.

The distribution of days with subzero temperatures in autumn and winter months (Table IX) shows drastic (highly significant) decline in these days in November, December, January and February of the last half of the century compared to the respective months of the first half of the century. However, in March and April the differences in days with subzero temperatures between first and second halves of the last century were not significant.

The climatic warming of the last half century over the first half century is reflected also in the monthly mean minimum temperatures of two main cold months, i.e. January and February (Table X). The number of years with less than zero monthly mean minimum temperatures in January have been reduced significantly from 9 in first half to 1 in the second half. Similar trend of monthly mean minimum

TABLE IX

Average number of days with subzero temperatures in different months during first and second halves of the study period

Period	November	December	January	February	March	April
1889–1943	1.5	6.4	9.8	6.3	1.7	0.09
1944–1998	0.9	4.1	7.2	4.2	1.7	0.07
1889–1998	1.2	5.2	8.5	5.3	1.7	0.08
t-value*	2.8	5.9	5.5	5.4	0.3	0.3
P-level	<0.00	<0.00	<0.00	<0.00	0.38	0.37

*t-values and P-levels to test the significance of the difference between means of periods 1889–1943 and 1944–1998.

TABLE X

Number of years with monthly mean daily minimum temperatures less than 0 °C

Period	December	January	February
1889–1943	1	9	4
1944–1998	0	1	1
t-value	1.0	2.7	1.4
P-level	0.16	<0.00	0.09

temperature in February was observed but at lesser significance (9% probability) and they reduced from 4 in first half to 1 in second half.

4. Conclusions

To understand the climatic variability at different time scales, time series of maximum, minimum and average temperatures were analysed at three different time scales, *viz*., short (20 years), medium (36–38 years) and long (55 years). The mean annual minimum temperatures over 20 years averaging period showed fluctuating trends up to early 1970s followed by steady increasing trend beyond. From the beginning, the mean annual maximum temperatures maintained steady increasing trend. The 20-year means of average temperature and diurnal temperature range also showed fluctuations in consecutive 20-year periods.

The annual means of minimum, maximum and average temperatures at medium scale also maintained higher means in the last one-third part of the last century compared to the means of respective parameters in the early part. At higher time scale (55 years) also these parameters registered higher annual means in the second half of the century than in the first half.

The analysis of the monthly means of minimum, maximum and average temperatures in all the calendar months at shorter time scale showed that the means of both minimum and maximum temperature of all the months in last 10-year period of the century are higher than the means of respective months exactly 100 years ago. While minimum temperatures could establish significant higher means in winter months (December–February), maximum could establish prominently higher means in winter as well as post-winter months (January–March) and summer (June–August) months.

The means of minimum temperatures at medium time scale displayed a definite increase in the months October–March and August of the last one-third part of the study period (1889–1998) compared to its first part where as the maximum temperatures could maintain significant increase in the months of January–April, July–August and October.

At longer time scale, though the means of both minimum and maximum temperatures in the second half of century are higher than the corresponding monthly means in the first half, they are more discernible in the winter months in case of minimum and in the months of January, February, April, May and July in case of maximum temperatures.

Trends of annual minimum temperatures at medium time scale showed cooling, normal and steep increasing trends in first, second and third parts of the century, respectively. The maximum temperature, however, established increasing, normal and steep increasing trends in first, second and third parts, respectively. Significant increasing trend of average temperatures was also noticed towards the last part of the century (study period).

The increasing trend in minimum, maximum and average temperatures during the last four decades were worked out to be 0.4, 0.43 and 0.4 °C per decade, respectively. If this increasing trend in temperature continues unabated, the annual temperature at the end of the 21st century will be increased by 4 °C, similar to the expected global-level temperatures.

The minimum, maximum and average temperatures over longer time scale (55 years) could establish statistically significant positive trends in the second half of the century. They could also establish significant warming trends to the tune of 0.01 °C per year over the whole century (study period).

The number of low-temperature extremes like frost days in first and second half of century also depicted the signals of global warming and the number of days with partial frost (minimum temperature < 0°C) drastically declined in second half compared to the first half. The decline in the days with subzero temperatures in main winter months of the later half of the study period when compared to the early half also reveals the symptoms of climatic change that might be taking place due to either urbanisation effects or large scale circulation changes or both.

The positive temperature changes at short, medium and long time scales and also reduction in the low-temperature extremes in the last four decades of the 20th century, are some indications of climate change that is taking place in this region. As Yan et al. (2002) reported that single site results (2 sites in Italy are also included in their study) are representative of larger regions, the indications of climate change at Firenze may have more than local implications and represent larger area.

The changes (increase) occurring in minimum, maximum and average temperatures in the past four decades will have lot of implications on agricultural crops with respect to their growth, development and productivity. The decline in low-temperature extremes like frosts will have beneficial effect. The changes in the start, end and length of growing season of winter crops are likely to occur. The introduction of new crops and varieties and change of prevailing crops may be possible in future. However, the beneficial effect of frosts like killing of pests will be minimised with the decline of frost days. The detailed discussion on the impact of these changes observed in temperature in conjunction with changes in precipitation will be reserved for the next article in this series.

This study emphasizes the need for identifying the physical or climatic systems that are causing variability only in minimum temperature but not in the maximum temperature, at shorter time scale. The causes for the climatic change that is undergoing in the last four decades should be understood in terms of anthropogenic and naturally occurring phenomena.

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