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Trends in surface temperature variability over Mumbai and Ratnagiri cities of coastal Maharashtra, India

MAHENDRA S. KORADE and AMIT G. DHORDE

Department of Geography, Savitribai Phule Pune University, Pune – 411 007, India

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e mail : amitdhorde@unipune.ac.in

सार – शहरीकरण में वृद्धि और नगरों के विस्तार के कारण शहरी उष्ण द्वीप (UHI) में तीव्रता आई है। शहर में और उसके आसपास जीवाश्मी ईंधन की अधिक उपयोगिता तथा विकिरण युक्त उष्णता के पाश होने के कारण सतही तापमान में वृद्धि होती है। इस शोध पत्र में मुंबई और रत्नागिरी शहरों के तापमान की परिवर्तिता पर प्रकाश डाला गया है जो समान तटीय जलवायविक क्षेत्र तथा लगभग समान तुंगता पर स्थित हैं। वार्षिक और मौसमी पैमाने पर अधिकतम और न्यूनतम तापमान की प्रवृत्तियों की जाँच की गई है। तापमान की चरम स्थितियों की घटनाओं का भी विश्लेषण किया गया। सामान्यत: दोनों केंद्रों में तापमान में वृद्धि की प्रवृत्तियाँ देखी गई जिसमें 95 प्रतिशत विश्वसनीयता स्तर पर सांख्यिकीय रूप से महत्वपूर्ण न्यूनतम तापमान की तुलना में अधिकतम तापमान में वृद्धि की अधिक दर पाई गई। रत्नागिरी की तुलना में मुंबई में अधिक दर पर उष्णन हुआ। मुंबई में उष्णता की चरम स्थितियों में भी महत्वपूर्ण रूप से वृद्धि हुई। रत्नागिरी में मॉनसून के दौरान गर्म दिनों और ग्रीष्म में शेष ऋतु के दौरान गरम रातों में कमी देखी गई।

ABSTRACT. Increasing urbanization and expansion of cities has led to intensification of the urban heat island (UHI). High consumption of fossil fuels and trapping of radiated heat leads to increase in surface temperature in and around city. Present research paper focuses on temperature variability over Mumbai and Ratnagiri cities, which are located in the same coastal climatic region and almost at same altitude. Trends in maximum and minimum temperature were investigated at annual and seasonal scale. The occurrences of temperature extremes were also analysed. In general, increasing trends were observed over both the stations, with high rate of increase in maximum temperature than the minimum temperatures statistically significant at 95% confidence level. Mumbai experienced significant warming with higher rates than Ratnagiri. Warm extremes have also increased significantly over Mumbai. Ratnagiri showed decrease in hot days during monsoon and hot nights during remaining seasons significant in summer.

Key words – Temperature trends, Extremes, Heat and cold waves, Mumbai, Ratnagiri.

1. Introduction

Though the surface air temperature of the earth is increasing, trend and magnitude vary at different places. Anthropogenic activities are found to be significantly affecting our environment and therefore, increasing human interference in the constitution of atmosphere is viewed with great concern by the climatologists. Researchers are engaged in identifying trends and shift in temperature using various statistical and stochastic techniques. Changing climate leads to changes in the frequency, intensity, spatial extent, duration and timing of extreme weather and climate events which tends to increase vulnerability for coastal cities (IPCC, 2012). An inconsistent climatic response to urbanization is also observed at these cities. Northern hemisphere land has warmed considerably faster than the Southern hemisphere land since the mid-1980s and 1990s have been the warmest decade of the millennium.

As the effects of climate change are threatening for the human society, significant research has been done to assess the trends in climatic parameters at different levels. Some studies related to surface temperatures conducted over different parts of the globe are mentioned here. Analysis of maritime, central and rocky mountain climatic zones of USA and Canada showed highest warming rates during winter in the maritime zone and at lower elevations in all zones and lowest warming rates occurred in autumn in the Rockies (Mote, 2003). Temperature over Malta (central Mediterranean) showed increasing trend of 1.1 °C during 1951-2010 (Galdies, 2012). Kousari *et al*. (2011) surveyed temperature changes over Iran during 1951-2005. The results showed rising temperature trends over the centrally located stations along with the eastern and northern ones. Most of the stations in Zagros showed no significant temperature changes. But Ghahraman (2006) concluded most of the stations showed positive trends in temperature over Iran. According to Chung *et al*. (2004)

effect of urbanization on temperature was common in all months except April over Korea. Switzerland witnessed warming with 0.135 °C per decade during 20th century, but this rate further increased up to 0.57 °C per decade during 1975-2004 (Rebetez and Reinhard, 2008).

During the past century India has experienced increase in mean annual temperature mostly over west coast, interior peninsula, north central and north-east regions of the country (Hingane *et al.*, 1985). Mean annual temperature over India has showed significant warming trend of 0.05 °C/10yr during the period 1901-2003, the recent period 1971-2003 has seen a relatively accelerated warming of 0.22°C/10yr, which was largely due to unprecedented warming during the last decade (Kothawale and Rupa Kumar, 2005; Nair and Hosalikar, 2013). Dhorde *et al.* (2009) analyzed long term temperature trends over a set of four largest cities of India. They reported an increasing trend in the mean annual temperatures of Delhi, Kolkata, Mumbai and Chennai. As far as warming is concerned, the effect of urbanization was more pronounced during post-monsoon and winter seasons. In addition to these, records of Chennai showed high rise in temperature during winter season with 1.3, 1.6 and 1.0 °C increase in mean annual, mean maximum and mean minimum temperature respectively during 1951-2010 (Jeganathan & Andimuthu, 2013). Changes in extreme weather are not uniform over the globe, but they are sensitive to human society, its infrastructure and environment. By definition, an extreme weather event is one which doesn't commonly occur at a given place and in a given season, and it is extreme only in relative sense. Few studies have shown increase in hot extremes and decrease in cold extremes over India (Pal and Al-Tabbaa, 2010), in future also these changes are likely to continue and India will experience widespread warming through extreme conditions (Kothawale *et al.*, 2010; Revadekar *et al.*, 2012). The purpose of this research was to understand and compare different tendencies of temperature and frequency of high and low temperature extremes at Mumbai and Ratnagiri for the period 1969 to 2006.

Mumbai is the economic capital of India, it owed its wealth to its historical colonial past, textile mills and the seaport, but the local economy has since been diversified and now Mumbai is home to most of India's specialised technical industries, having modern industrial infrastructure and large skilled human resource. The city grew during British rule, as variety of services grew up around the port and continued to grow after British left in 1947. Since 1971, Mumbai experienced inexorable rise in the population, from 8 million in 1971 to 21 million now. Ratnagiri city is the head quarter of district Ratnagiri. Though Ratnagiri Municipality was established in 1876, the town did not witness rapid urbanization like Mumbai. According to 2011 census population of Ratnagiri city was 76,229. Thus, as compared to Mumbai this city is much smaller and therefore, it would be interesting to know temperature trends there.

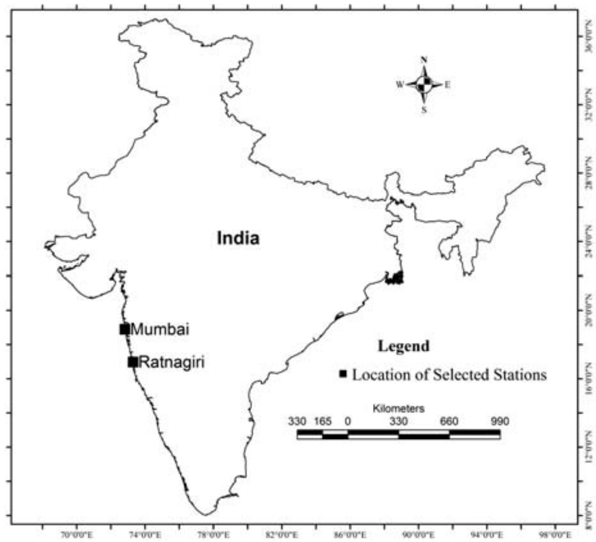


Fig. 1. Location map of weather stations selected for study

2. Data and methodology

The daily time series of maximum temperature (*Tmax*) and minimum temperatures (*Tmin*) for both the meteorological stations of Mumbai (Colaba) and Ratnagiri were analyzed for the period 1969-2006. Both these stations belong to the same physiographic division and are characterized by similar climatic conditions. Their location is illustrated in Fig. 1. Though the observations are available for longer periods, the study region saw a burst of industrialization and urbanization during the study period (Kothawale and Rupa Kumar, 2005; Nair and Hosalikar, 2013) and according to IPCC (2007) fourth assessment report steep change was noticed in annual global temperature around 1975 after a cooling period during 1940 to 1970. Hence, it is felt that the period 1969-2006 can cover the quick change in temperature trends (Nair and Hosalikar, 2013). Daily temperature series for the study period were obtained from the National Data Center of India Meteorological Department (IMD), Pune. Missing values were incorporated in the series if the year's records were incomplete. Double mass curve method and correlation analysis were applied to check the homogeneity of data series. It is a graphical method used for identifying inconsistency in a weather station data by comparing it with nearby relatively stable weather station data (Tabari *et al.*, 2011). Daily values were averaged to obtain monthly, seasonal and annual series according to

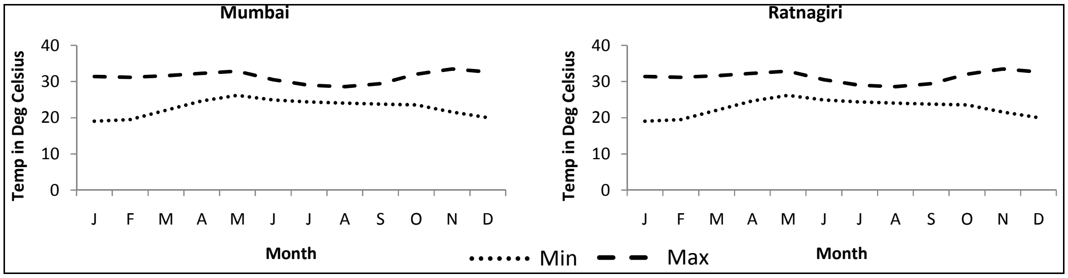


Fig. 2. Annual cycle of minimum and maximum temperature at Mumbai and Ratnagiri

requirement of statistical test. The four seasons have been defined as winter (December-February), summer (March-May), monsoon (June-September), and post-monsoon (October-November).

Through observations data were checked for gross errors like temperature values exceeding unlikely threshold values over the region. Given climatology of the region, *T*max over Mumbai and Ratnagiri are not expected to exceed 45 °C and *Tmin* were checked for a lower threshold of 0 °C (Nair and Hosalikar, 2013). Fig. 2 shows the annual cycles of temperature over Mumbai and Ratnagiri, coastal stations of Maharashtra.

The decadal variability of temperature anomalies for both *Tmax* and *Tmin* were analysed for each decade (the last decade included 8 years to adjust the 38 year period) at Mumbai and Ratnagiri. Linear regression method was used for evaluating the trends and the rate of change was calculated through the slope of the regression line. The statistical significance of the trends was assessed by using a two-tailed *t*-test at 95% confidence level. Linear trends of temperature were used to depict the seasonal changes at both the stations. Obtained temperature trends were used to understand the absolute shifts in temperature at seasonal and annual scale.

Extreme temperature events for the present study were based on the percentile method wherein an extreme event was defined as a value which exceeds the 90^{th} percentile or falls below the 10^{th} percentile. The 90^{th} and the 10^{th} percentiles were calculated for each calendar day and the following temperature indices were derived.

Hot day : Daily *Tmax* exceeding the 90^{th} percentile of *Tmax*

Hot Night : Daily *Tmin* exceeding the 90^{th} percentile of *Tmin*

Cold Night : Daily *Tmin* below the 10^{th} percentile of *Tmin*

Monthly frequencies of hot/cold days and nights were estimated with the above defined thresholds and later cumulated to form the seasonal time series. This time series of frequencies of extreme temperature events was analysed for long term trend, which was expressed as days/year. The trends obtained for extreme event were also tested for statistical significance by using a two-tailed *t*-test at 95% confidence level.

TABLE 1

Criteria for heat wave category

Heat wave category	Departure from normal temperature (> 40 °C)	Departure from normal temperature (< 40 °C)
Slight	3-4	4-5
Moderate	4-5	5-6
Severe	>5	>6

TABLE 2

Criteria for cold wave category

Cold wave category	Departure from normal temperature (< 10 °C)	Departure from normal temperature (> 10 °C)
Slight	1-3	3-5
Moderate	3-5	5-7
Severe	>5	>7

Monthly and decadal heat and cold waves were calculated as per the guidelines given by IMD. Heat waves and cold waves were classified in to three categories, *i.e.*, Slight, Moderate and severe, criteria for which are given in Table 1 and 2.

3. Results and Discussion

Mumbai and Ratnagiri cities are situated on the west coastal region of India and have same physiographic and climatic conditions. Annual cycle of *Tmin* and *Tmax* reflects same cyclic pattern at both the stations (Fig. 2). Lowest monthly *Tmin* is observed in the month of January and after that it goes on increasing up to May which showed highest mean monthly *Tmin*, later *Tmin* decreases up to January. However, mean monthly *Tmax* curve was bimodal, picks were observed in the month of May and November.

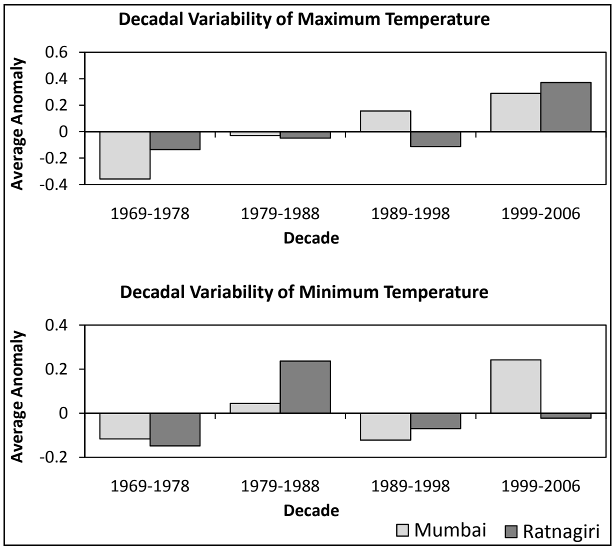


Fig.3. Decadal variability of minimum and maximum temperature at Mumbai and Ratnagiri

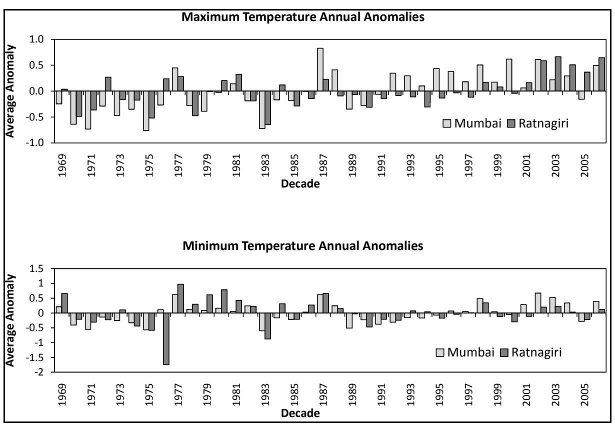


Fig. 4. Annual anomalies for *T*max and *T*min at Mumbai and Ratnagiri relative to the period 1969-2006

3.1. *Decadal trends in temperature variability*

Decadal variations in *Tmin* and *Tmax* anomalies are shown in Fig. 3. Both the stations experienced same phases of variations in decades, except in the decade 1989-98 for *Tmax* and last decade for *Tmin*. The average *Tmax* anomalies at Mumbai station were negative for the first two decades and positive for the remaining two decades. However, at Ratnagiri it turns positive only in the fourth decade. The average *Tmin* anomalies were negative for the first and last two decades at Ratnagiri and positive for the second decade. On the other hand, at Mumbai, the changes were alternative, negative for first and third decades and positive in the second and forth decades. Highest anomalies in *Tmax* were observed in last decade at both the stations. In case of *Tmin*, largest anomalies were observed at Mumbai station in the last decade whereas at Ratnagiri it was observed in the second decade.

TABLE 3

Annual and seasonal linear trends in *Tmin* and *Tmax* at Mumbai and Ratnagiri

Season	*Tmax* trends (^{o}C/Decade)		*Tmin* trends (^{o}C/decade)	
	Mumbai	Ratnagiri	Mumbai	Ratnagiri
Annual	0.24*	0.13*	0.1*	0.01
Winter	0.44*	0.32*	0.11	-0.009
Summer	0.21*	0.08	0.09	-0.22
Monsoon	0.05	0.004	0.09*	0.07
Post-Monsoon	0.38*	0.23*	0.14	0.27

*significant at 0.5 level

TABLE 4

Rate of change in occurrences of temperature extremes over Mumbai and Ratnagiri

Season	Mumbai (days/decade)			Ratnagiri (days/decade)		
	Hot days	Hot night	Cold nights	hot days	Hot night	Cold nights
Winter	3*	1	-1	3*	-1	-1
Summer	3*	2	-1	2*	-4*	1
Monsoon	1	1	-2	-1	0.0	-4*
Post-Monsoon	1	1	-2*	2	-1	-3*

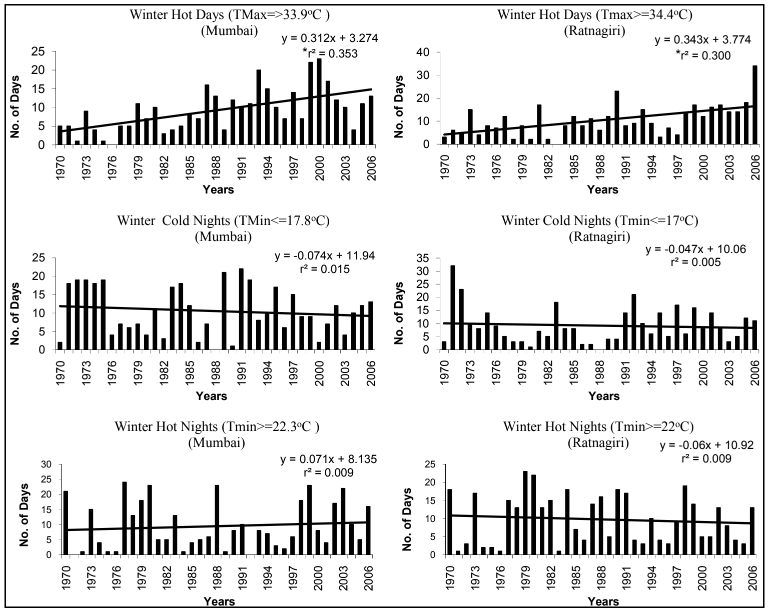
*significant at 0.5 level

3.2. *Annual trends in temperature variability*

Yearly variability in *Tmax* and *Tmin* are shown in Fig. 4. The anomalies for *Tmax* were constantly negative for first two decades which shifted to positive in the last two decades at Mumbai, whereas at Ratnagiri the anomalies remained negative for first three decades and became positive after 1997. *Tmin* annual anomalies did not show continuous pattern, but at Mumbai it showed a clear warming trend after the second decade whereas *Tmin* anomalies for Ratnagiri did not have any visible trend.

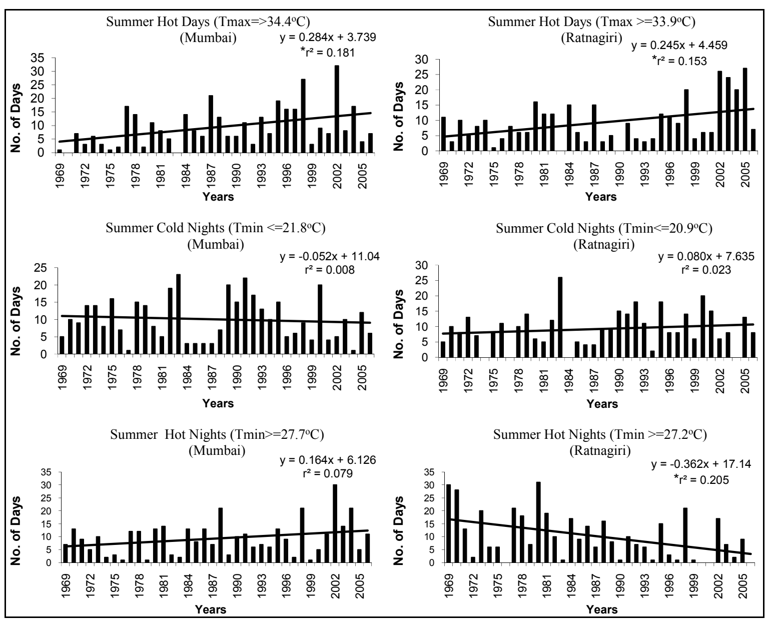
3.3. *Linear trends in annual and seasonal temperature*

Linear trends in temperature at annual and seasonal scales were computed and significance of trend was evaluated using student *t*-test; results are mentioned in Table 3. All annual trends were positive and significant except *Tmin* at Ratnagiri. Amusingly, Mumbai showed double rate of increase in annual *Tmax* and ten times higher warming in annual *Tmin* compared to Ratnagiri. This enormous warming may be attributed to rapid urbanization because some studies have mentioned that



*significant at 0.5 level

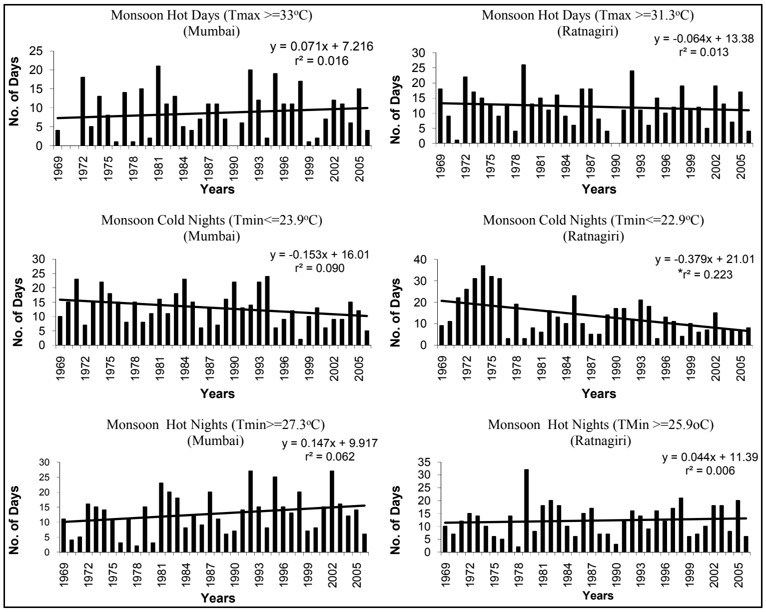
Fig. 5. Trends in temperature extremes during winter season



*significant at 0.5 level

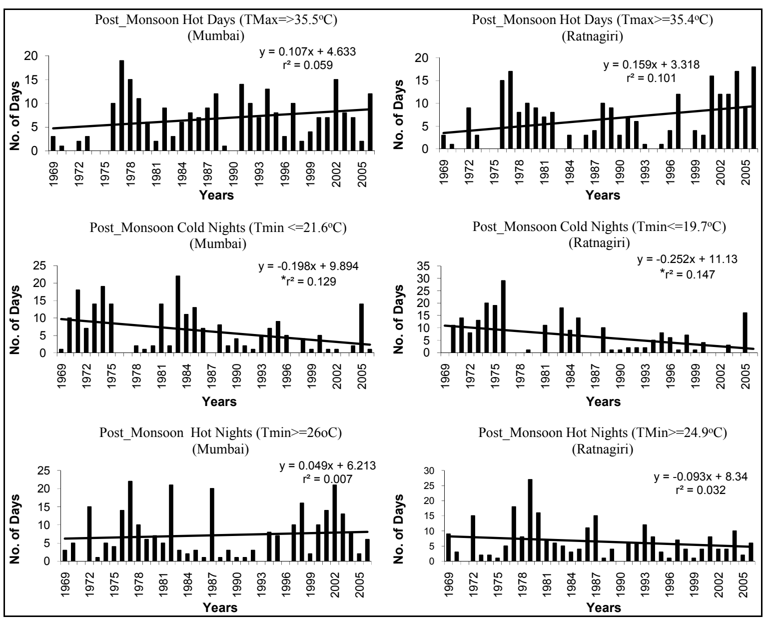
Fig. 6. Trends in temperature extremes during summer season

there is strong impact of urbanization on temperature. Chung *et al*. (2004) studied mean monthly temperature over Korea and concluded that up to 0.5° warming of nighttime temperature was induced by urbanization in the 1971-2000 period compared with the 1951-1980. Highest warming rate at both the stations has been observed during winter *Tmax* (Table 3). *Tmax* at Mumbai showed significant warming trend in all seasons except monsoon, whereas in case of *Tmin* only monsoon season showed significant warming trend. Overall diurnal range of temperature increased at Mumbai due to rapid increase in *Tmax* compared to *Tmin. Tmax* over Ratnagiri increased significantly during winter and post- monsoon seasons while non-significant positive trends were observed during summer and monsoon seasons with negligible rate of change. Winter and summer *Tmin* over Ratnagiri



*significant at 0.5 level

Fig. 7. Trends in temperature extremes during monsoon season



*significant at 0.5 level

Fig. 8. Trends in temperature extremes during post-monsoon season

showed negative trends and positive trends were observed during monsoon and post-monsoon, but all trends were non-significant.

3.4. *Trends in extreme temperature*

The trends in three extremes were calculated for four seasons and results are presented in Table 4. Rate of change in occurrences of temperature extremes were further evaluated by *t*-test to check the statistical significance of trend.

3.4.1. *Winter*

Trends in temperature extremes for both Mumbai and Ratnagiri are shown in Fig. 5. Winter hot days tend to

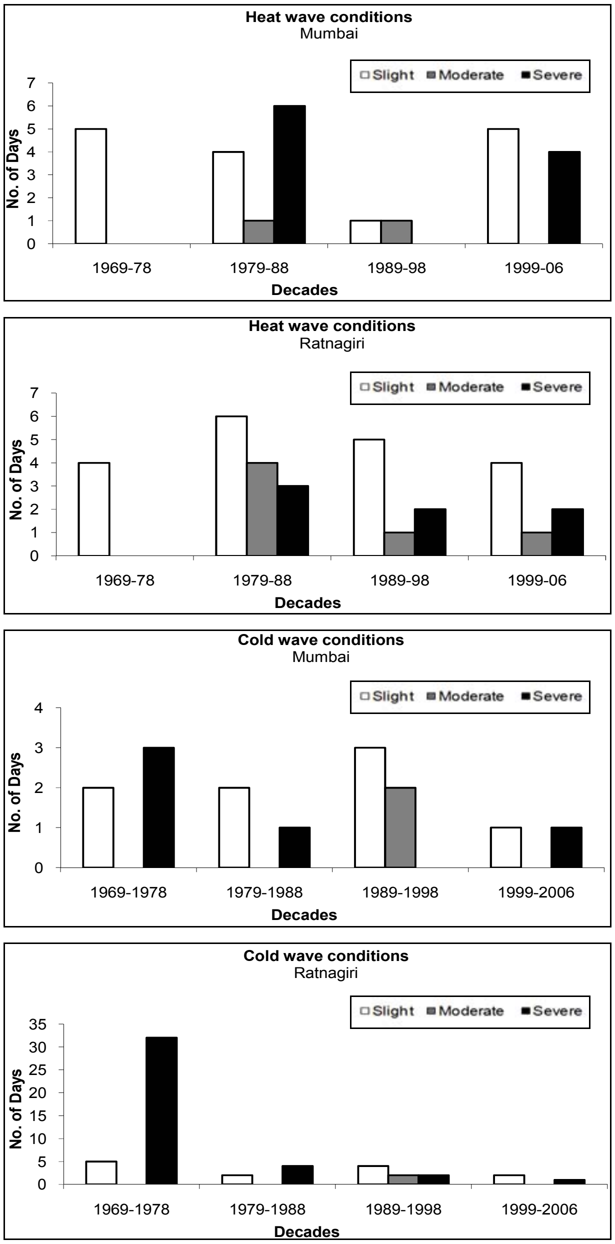


Fig. 9. Decadal distribution of occurrences of heat and cold waves at Mumbai and Ratnagiri

increase at both Mumbai and Ratnagiri by 3 days/decade and were found to be statistically significant at 95% confidence level (Table 4). Both the stations showed a tendency for cold nights to decrease, but the trends were not significant. Winter hot nights increased in Mumbai while Ratnagiri showed decreasing trend.

3.4.2. *Summer*

Fig. 6 shows trends in extreme temperature events for the summer season. During the summer season trend in occurrence of hot days over both the stations showed a remarkable increase. Mumbai getting warmer through increasing frequencies of hot days with the rate of 3 days/decade as well as Ratnagiri with 2 days/decade and both were statistically significant (Table 4). During the night at Mumbai, results showed increase in frequency of hot nights and decrease in frequency of cold nights. Contradictory to this, results for Ratnagiri showed significant decreasing trend in the hot nights with the rate of 4 days/decade which is supportive to increase in cold nights. The effect of urbanization on night temperatures can be clearly observed at Mumbai.

3.4.3. *Monsoon*

Fig. 7 shows trends in temperature extremes during monsoon. The frequency of hot days and hot nights at Mumbai showed increasing trend whereas cold nights showed decreasing trend. The frequency of cold nights and hot days at Ratnagiri station showed similar trend but cold nights showed noticeable decrease of 4 days/decade (Table 4). Only hot nights slowly increased at Ratnagiri.

3.4.4. *Post-Monsoon*

Fig. 8 shows trends in temperature extremes during post-monsoon season. The frequency of hot days showed a tendency to increase and the frequency of cold nights showed declining trend at both the stations. Trends in occurrence of cold nights at both stations were statistically significant but the results for hot days were non-significant. Hot nights showed a tendency to increase at Mumbai station though the increase was not significant. Hot nights at Ratnagiri station however showed a greater tendency to decrease. Cold nights decreased in all seasons, significant in post-monsoon at Mumbai.

3.5. *Decadal variation in heat and cold wave*

Daily temperature data were evaluated for heat and cold waves and summed up at decadal scale based on the criteria mentioned in Tables 1 & 2. Results are illustrated in Fig. 9. During the study period, number of days with heat wave condition over Ratnagiri were more than the Mumbai but the frequency of heat waves decreased over Ratnagiri in all categories, *i.e.*, slight, moderate & severe, where as frequency of heat waves over Mumbai does not shows any pattern. Cold waves decreased at both the stations but remarkably Ratnagiri showed sudden decrease in severe cold waves during second decade and slow but constant decrease later on. Overall, cold waves over Mumbai showed decreasing pattern. This again confirms the effect of urbanization over minimum temperature.

4. Conclusion and summary

The main objective of this research was to investigate the nature of changes in the temperature trends of Mumbai and Ratnagiri in recent decades. *Tmax* annual anomalies showed clear increasing trend which began early at Mumbai. Significant annual warming trend was observed in night-time temperature at Mumbai and in day-time temperature at both the stations. Seasonal peculiarities in rate of change was common feature at both the stations; day time warming was more predominant with double rate at Mumbai. Non-significant trends were observed in all seasons with negative trends in winter and summer at Ratnagiri. The effect of this changes in temperature was reflected in number of hot days. All seasons showed increase in hot days at both the stations, except during monsoon at Ratnagiri. Except summer, all seasons experienced decrease in cold nights, significant during monsoon and post-monsoon at Ratnagiri. Hot nights increased in all seasons at Mumbai and in monsoon at Ratnagiri. Occurrences of cold wave decreased considerably at both the stations.

In summary, Mumbai and Ratnagiri have shown clear signs of warming with pronounced seasonal distinctions with highest warming rate during winter at Mumbai and post-monsoon at Ratnagiri. The rate of warming is more in day-time temperatures as compared to the night-time temperatures. These changes in temperature may lead to increases in warm extremes and decreases in cold extremes which are observed at both the stations. Overall, Mumbai is warming twice the rate at Ratnagiri which may be chiefly due to the effects of urbanization and industrialization.

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