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ORIGINAL PAPER

Spatial distribution of temperature trends and extremes over Maharashtra and Karnataka States of India

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Abstract Earth surface temperatures are changing worldwide together with the changes in the extreme temperatures. The present study investigates trends and variations of monthly maximum and minimum temperatures and their effects on seasonal fluctuations at different climatological stations of Maharashtra and Karnataka states of India. Trend analysis was performed on annual and seasonal mean maximum temperature (TMAX) and mean minimum temperature (TMIN) for the period 1969 to 2006. During the last 38 years, an increase in annual TMAX and TMIN has occurred. At most of the locations, the increase in TMAX was faster than the TMIN, resulting in an increase in diurnal temperature range. At the same time, annual mean temperature (TM) showed a significant increase over the study area. Percentiles were used to identify extreme temperature indices. An increase in occurrence of warm extremes was observed at southern locations, and cold extremes increased over the central and northeastern part of the study area. Occurrences of cold wave conditions have decreased rapidly compared to heat wave conditions.

1 Introduction

Increase in global surface air temperature during the recent decades is one of the most sensitive issues of recent times. Temperature is an end result of an integral component of climate variability and change on local, regional, and global scale. Documentation shows changes in climate at many locations throughout the world (Jeganathan and Andimuthu 2012). But, the trends are variable depending on seasonal and annual patterns and are greatly modified by altitude and location in relation to the sea coast and other such geographical features (Pal and Al-Tabbaa 2010). Extremes in temperature are characterized by daily temperature level exceeding tolerance limits and their frequency is of great interest in terms of human impacts (Revadekar et al. 2012). Observations gathered since 1950 give evidence of change in some extremes, but the observed changes in extremes depend on the quality and quantity of data as well as the availability of studies analyzing these data, which vary across regions and for different extremes (IPCC 2011). Change in temperature and their extremes have major socio-economic implications such as their direct impact on availability and use of water, power generation and consumption, crop yield, human health and comfort, etc. (Meehl et al. 2000). Therefore, detailed impact assessments require information on changes in climatic variability at local, regional, and national scale. It is obligatory to analyze changes in mean temperature (TM) along with trends in variability of climatic variables, since variability is a key to judge the change in climate. Results of some studies from different regions of the world are summarized below.

Trends of extreme temperatures in Europe and China showed decreasing warm extremes before the late nineteenth century and decreasing cold extremes along with increasing warm extremes since the 1960s (Yan et al. 2002). However, all temperature indices of climate extremes show statistically significant warming trends over the arid region of northwest China during 1960 to 2003 (Wang et al. 2012). Warm extremes in temperature have increased over the dry surface of North Africa, and more moderate increases in extreme temperature over the west coast of North America are observed

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(Meehl et al. 2000). Occurrence of winter extremes in Central Spitsbergen show a significant increasing trend in mean winter temperature of approximately 1.65 °C per decade from 1975–76 to 2007–08. At the same time, significant decreasing trend in number of days with extremely low mean daily temperatures was observed at a rate of approximately 5 days per decade (Bednorz 2011). A study of temperature extremes in South America for the past four decades indicates increasing warm nights and decrease in cold nights (Vincent et al. 2005).

Temperature trend analysis of many regions using observed temperature data have already showed some significant changes in temperature extremes. Since the second half of the nineteenth century, global TM has increased by 0.7 °C (Nicholls et al. 1996; Parker et al. 2000). Most of the Northern Hemisphere and Australia registered increasing temperatures over the period from 1946 to 1999 (Frich et al. 2002). The mean annual temperature of Pakistan increased around 0.36 °C/decade during 1952–2009 (Del Rio et al. 2013). In many parts of the world, intra-annual extreme temperature range shows a systematic and statistically significant decline over the past four to five decades (Frich et al. 2002). Long-term trends in climatic variables in Iran depict a warming trend in annual mean, annual maximum, and annual minimum temperature at majority of the stations which mostly began from 1970s (Tabari et al. 2011). Shanxi Province of China experienced increasing trends of the annual mean maximum temperature (TMAX) and mean minimum temperature (TMIN) over the past 50 years. Significant positive trends were also observed in warm days and nights, the highest and lowest maximum and minimum temperatures, and significant negative trends were revealed for cold days and nights (Fan et al. 2012).

A study on climate variability over India has revealed that mean annual and seasonal temperatures show a significant rising trend in all seasons (Subash et al. 2011). During the past century, India has experienced increase in annual TM by 0.4 °C (Hingane et al. 1985). Dhorde and Wakhare (2009) identified ten distinct clusters for India based on spatial variations in the rates of temperature change. Increase in annual TM over the southern peninsula cluster is due to higher and significant rise in maximum temperature at majority of locations with few cities also registering increase in minimum temperature. According to another study, India has experienced increase in annual TM by 0.42 °C, rise of 0.92 °C in the annual TMAX, and a rise of 0.09 °C in TMIN during the last 100 years (Arora et al. 2005). Extreme temperatures from 1901 to 2003 show positive significant trends in all months; observed data also depicts increase in maximum temperature as much as 1.90 °C in 100 years during November and 1.79 °C in 100 years during February over the west coast, whereas the interior peninsula observed positive significant trends in all months except April and May (positive but not significant) and June and August (no trend) (Pal and Al-Tabbaa 2010). These changes are also likely to continue in the future, and India will experience widespread warming through increase in intensity and frequency of hot events and also with decrease in frequency of cold events (Revadekar et al. 2012). 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 does not commonly occur at a given place and in a given season, and it is extreme only in a relative sense. With this in the background, the recent study focused on frequency of high and low temperature extremes at selected stations over Maharashtra and Karnataka states. Because of various reasons, meager information is available about trends in extreme temperature in the Asia-Pacific region (Manton et al. 2001). Therefore, it is necessary to monitor extreme events and find the changes in extremes. The primary objective of this study is to examine the changes in temperature trends and extremes over Maharashtra and Karnataka states of India during the period 1969–2006.

2 Data and analysis techniques

Daily maximum and minimum temperature data for the period between 1969 and 2006 of 21 stations belonging to the states of Maharashtra and Karnataka (Fig. 1) were collected from the National Data Center (NDC) of the India Meteorological Department (IMD). The stations were selected based on spatial distribution and availability of data. Missing values were incorporated from daily weather reports published by IMD. Double mass curve method (Kohler 1949) and correlation analysis (Bhutiyani et al. 2010) were applied to test homogeneity of the data. It is a graphical method used for identifying inconsistency in weather station data by comparing them with the neighboring relatively stable weather station data (Tabari et al. 2011). Monthly, seasonal, and annual series were constructed from the daily values. Statistical analysis was carried out for four seasons which have been defined as winter (December–February), summer (March–May), monsoon (June–September), and post-monsoon (October–November) (Jaswal et al. 2008; Korade and Dhorde 2016).

In order to describe the trends and their statistical significances, linear regression, Sen's slope estimator, and Mann-Kendall (MK) rank statistic test were used (Subash et al. 2011; Tabari and Talaee 2011; Zhang et al. 2011; Del Rio et al. 2013; Dhorde et al. 2014). MK test is widely used in environmental science, because it is simple and does not assume a distribution of residuals, it is robust to the effect of outliers in the series, and can cope with missing values and values below detection limit (Revadekar et al. 2012). Mann-Kendall test does not give the rate of change (Subash et al. 2011; Wang et al. 2012); therefore, a simple non-parametric procedure developed by Sen (1968) was used to estimate rate

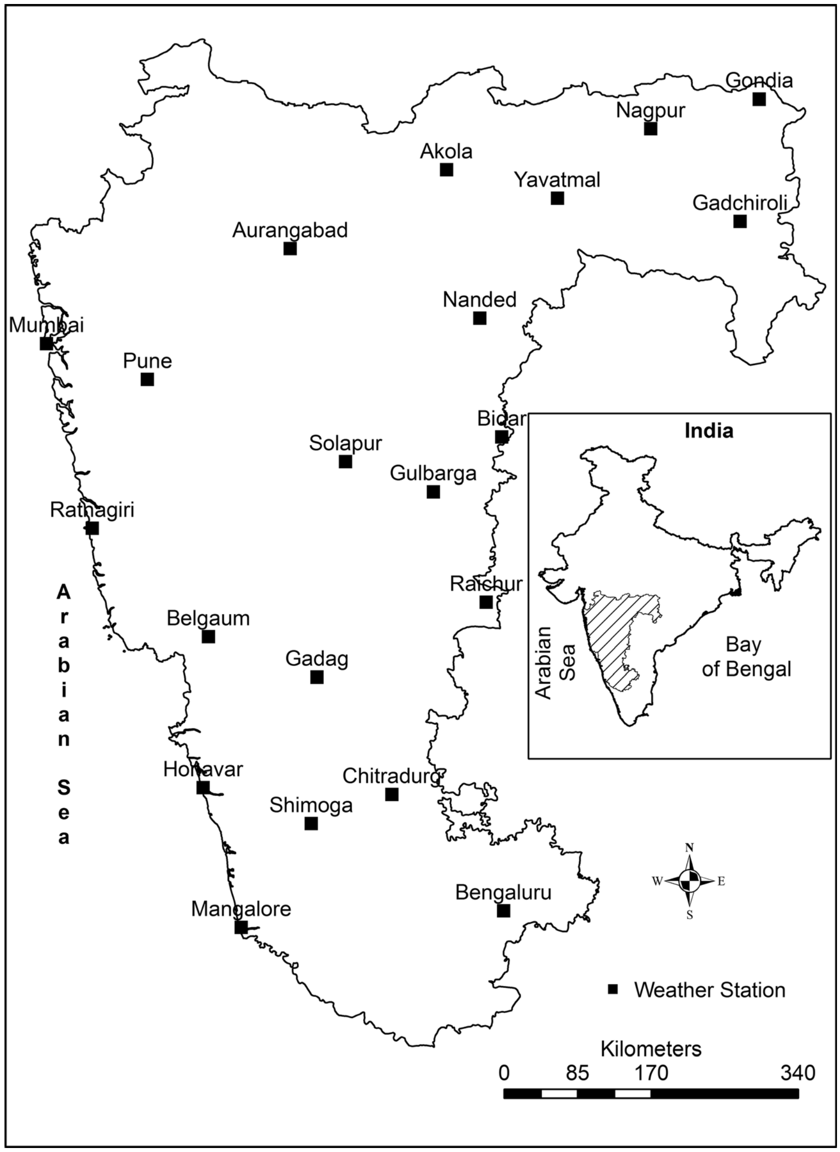


Fig. 1 Location of study area and weather stations

of change per unit time (Tabari and Talaee 2011). Linear least square method was used to detect the magnitude of trends, and significance of trends was tested with the help of standard Student's *t* test for all indices (Pal and Al-Tabbaa 2010).

The slope values obtained after applying linear regression were multiplied by "10" to determine decadal rate of change in TMAX, TMIN, and TM. A spreadsheet was prepared in MS Excel summarizing annual and seasonal temperature change at every station. This spreadsheet was attached to the attribute table of the shapefile prepared for showing station locations on a map. This analysis was done in ArcGIS 10.0 where "join" function can be used to attach MS Excel tables with the attribute table. Once the table was imported in ArcGIS, then the information in the attribute table (slope values) was used to prepare maps depicting trends in TMAX, TMIN, and TM. Similarly, changes in heat and cold waves were also mapped. For representing trends in hot and cold extremes, interpolation was done by employing ordinary kriging method in ArcGIS. According to Tabios and Salas (1985), kriging is superior to other commonly used interpolation techniques. It is a sophisticated geo-statistical technique which provides unbiased interpolation with minimum mean square estimation error (Holdaway 1996). Symbology function of ArcGIS 10.0 was extensively used to generate different maps represented in this study.

Heat and cold wave analysis was based on the guidelines given by IMD, Pune, in the Meteorological Terminology and Glossary (http://www.imdpune.gov.in/weather_forecasting/glossary.pdf). Heat and cold waves were classified in to three categories which are slight, moderate, and severe. Criteria for this classification are given in Table 1. IMD has defined moderate and severe categories, but to monitor minor fluctuations slight category of wave was also defined. Extreme temperatures were defined

Table 1 Criteria adopted for categorizing cold wave and heat wave

Cold/heat wave category	Cold wave		Heat wave	
	Normal temperature below 10 °C Below normal temperature (°C)	Normal temperature above 10 °C Below normal temperature (°C)	Normal temperature above 40 °C Above normal temperature (°C)	Normal temperature below 40 °C Above normal temperature (°C)
Slight	1–3	3–5	3–4	4–5
Moderate	4–5	5–6	4–5	5–6
Severe	>=6	>=7	>=6	>=7

according to the Intergovernmental Panel on Climate Change (IPCC) guidelines, as occurring with a frequency lower (higher) than or equal to 10th (90th) percentile (IPCC 2007; Yan et al. 2002; Gallant and Karoly 2010; Bednorz 2011; Revadekar et al. 2012; Wang et al. 2012; Fan et al. 2012). The 5th, 10th, 15th, 99th, 95th, and 90th percentile values of daily temperatures during the period 1969–2006 were determined for each month and seasonally cumulated to obtain a time series for all seasons at each station (Kothawale et al. 2010). Using these percentile values, the number of hot and cold days in daily maximum temperature and number of hot and cold nights in daily minimum temperature were identified for different months and seasons for the entire data period. The hot/cold days as well as hot/cold nights were used to estimate the frequencies of extreme temperature events. Specification of extreme temperature events are given in Table 2. Trends in temperature extremes were analyzed for each station and maps show their spatial distribution.

3 Results and discussion

3.1 Annual and seasonal temperature trends

Mean global surface temperature has increased remarkably during the late twentieth century and will continue to increase in the twenty-first century (WMO 2012). To determine whether the behavior of temperature over the study area resembles global trend, annual and seasonal mean temperatures were analyzed for trends. Figure 2 illustrates the average annual and seasonal temperature trends over the study area. It indicates a tendency towards warming in Maharashtra and Karnataka during the study period except the summer season. Annual TM increased by 0.11 °C per decade whereas winter TM by 0.21 °C per decade, both statistically significant at 99 % confidence level. Post-monsoon TM also registered similar increasing tendency with 95 % confidence level. Monsoon TM has increased while decreasing trend was observed in the summer season, but both were statistically insignificant. Figures 3 and 4 show the spatial distribution of trends in TM, TMAX, and TMIN for all seasons and annual series of temperature. It can be inferred from the figures that TMAX has increased at majority of locations compared to TMIN.

3.1.1 Annual

Figure 3a illustrates changes in annual TM. Results shows that 38 % of stations registered statistically significant rising trends and not a single station recorded a significant decreasing trend. Warming tendency in annual TM is more supported by day-time temperature (TMAX) than night-time temperature (TMIN) since 57 % of stations recorded a significant upward trend in maximum temperature. All coastal weather stations recorded increasing trends. On the contrary, stations located in the interior have registered both increasing as well as decreasing trends. Kothawale et al. (2010) also mentioned significant warming trend for the coastal region. The stations having warming trend are mostly located in southern part of the study area which belongs to Karnataka State. Positive significant trends in TMAX are observed over 57 % of stations and one station located in the eastern part of Maharashtra observed a significant decreasing trend. About 19 % of stations have recorded non-significant increase and decrease over the study area (Fig. 3b). Around 47 % of stations recorded negative trend in TMIN and the remaining stations experienced increase in temperature but all trends were not statistically significant except Mumbai, Bengaluru, and Aurangabad which had significant positive trends (Fig. 3c). Gentle increase in TMIN has also been reported by Arora et al. (2005).

3.1.2 Winter

Highest increases were observed in TMAX of the winter season. During this season, changes in TMAX ranged from −0.33 to 0.79 °C/decade. Almost 62 % of stations showed positive significant trends in TMAX which were concentrated in the southern part of the study area (Fig. 3e). Only three stations registered negative non-significant trends, located in the northern part of the study area. Bengaluru was the only exception, having significant increasing trend in TMIN. Non-significant decreasing (increasing) trends in TMIN were observed at 11 (9) stations (Fig. 3f).

3.1.3 Summer

As the warmest season, the result of summer TM did not show expected warming trends in the study area. Only Mumbai and Bengaluru recorded significant rising trends in temperature ranging between 0.15 and 0.17 °C/decade. The trend of summer TM at Nanded located in the interior region remarkably

Table 2 Criteria adopted for categorizing extreme temperature indices

Warm temperature percentiles		Cold temperature percentiles	
Index	Description	Index	Description
Extremely hot day	TMAX ≥ 99p	Very cold night	TMIN ≤ 5p
Very hot day	99p > TMAX ≥ 95p	Cold night	5Pp < TMIN ≤ 10p
Hot day	95p > TMAX ≥ 90p	Moderate cold night	10p < TMIN ≤ 15P

showed a decreasing rate of 0.81 °C/decade (Fig. 4a). Fifty-two percent of stations registered decreasing tendencies in summer TM. All significant trends in TMAX are positive (except Nanded) (Fig. 4b). Most of the stations showed opposite tendency in summer TMAX and TMIN. Some stations showed increasing trends in TMAX while some stations recorded decreasing trend in TMIN (Fig. 4b, c). The summer TMIN result showed decreasing trends at 71 % of weather stations. Kothawale et al. (2010) noticed that the seasonal TMIN has significantly increased over the west coast of India but the results of this study indicate three coastal stations (out of four) had decreasing trend in temperature.

3.1.4 Monsoon

Monsoon TM increased significantly at four stations located in the southern part of the study area, two stations located on the coast, and two in the interior (Fig. 4d). TMAX has significantly increased at Belgaum, Raichur, Shimoga, and Mangalore whereas significant increase in minimum temperature was recorded in the industrial cities of Mumbai, Aurangabad, and Bengaluru (Fig. 4e). Raichur registered the highest increasing rate in average monsoon temperature which is 0.39 °C/decade. Overall, more than 75 % of weather stations recorded a warming tendency in monsoon TM.

3.1.5 Post-monsoon

Warming trend was observed over the entire region in post-monsoon TM except Yavatmal where a non-significant negative trend in temperature was recorded (Fig. 4g). The coastal region is rapidly and significantly warming than the interior parts throughout the study period. Out of four stations on the coast, three stations showed a significant increase in post-monsoon TM. The range of warming in this season is marked from 0.03 to 0.47 °C/decade during the study period. Post-

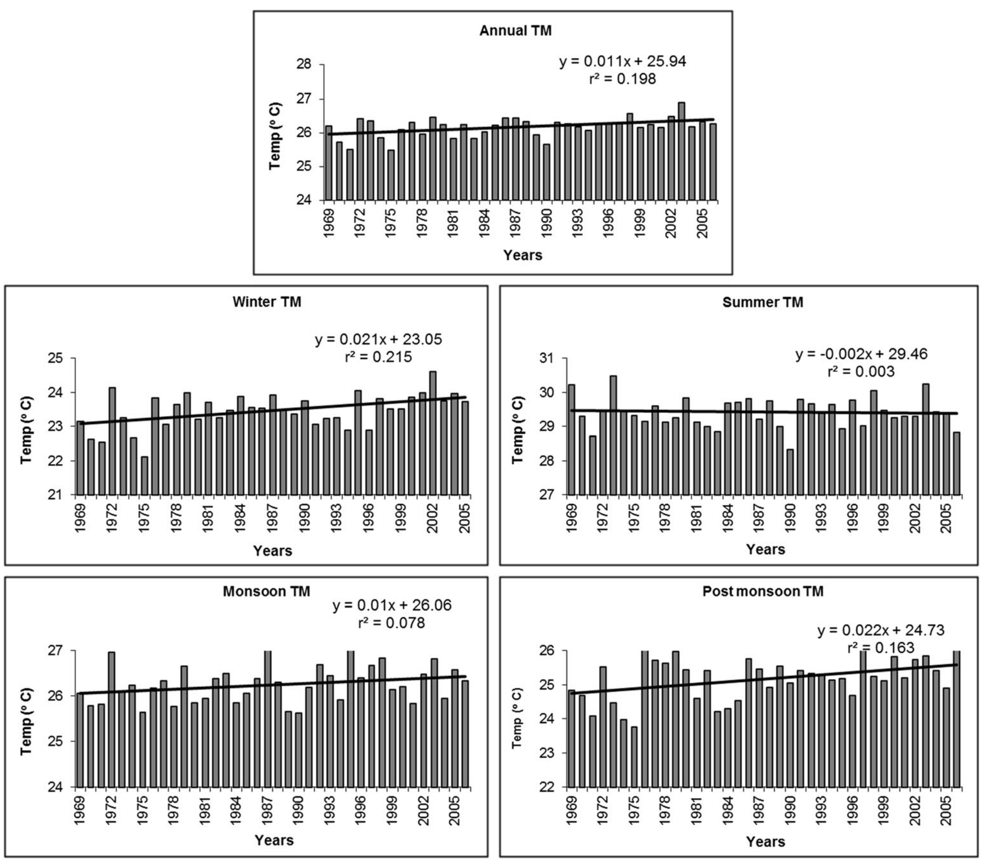


Fig. 2 Mean annual and seasonal temperature trends over study area

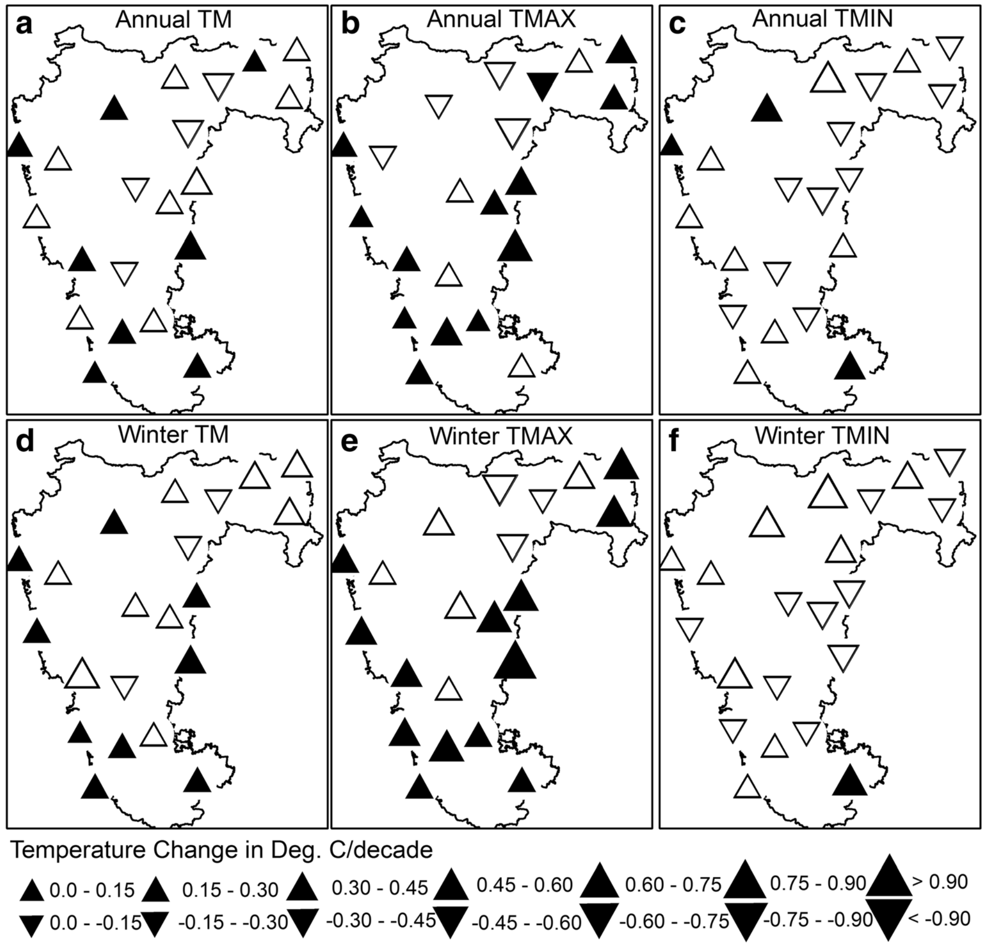


Fig. 3 Trends (in degrees Celsius per decade) in Annual (**a–c**) and winter (**d–f**) temperature significant at 95 % confidence level. *Filled triangles* indicate significant trends and *hollow triangles* indicate insignificant trends

monsoon TMAX results showed positive significant trends at 42 % of stations while positive non-significant trends at 38 % of stations (Fig. 4h). Nearly 20 % of stations showed a non-significant decreasing trend in TMAX which were concentrated in the northern parts of the study area.

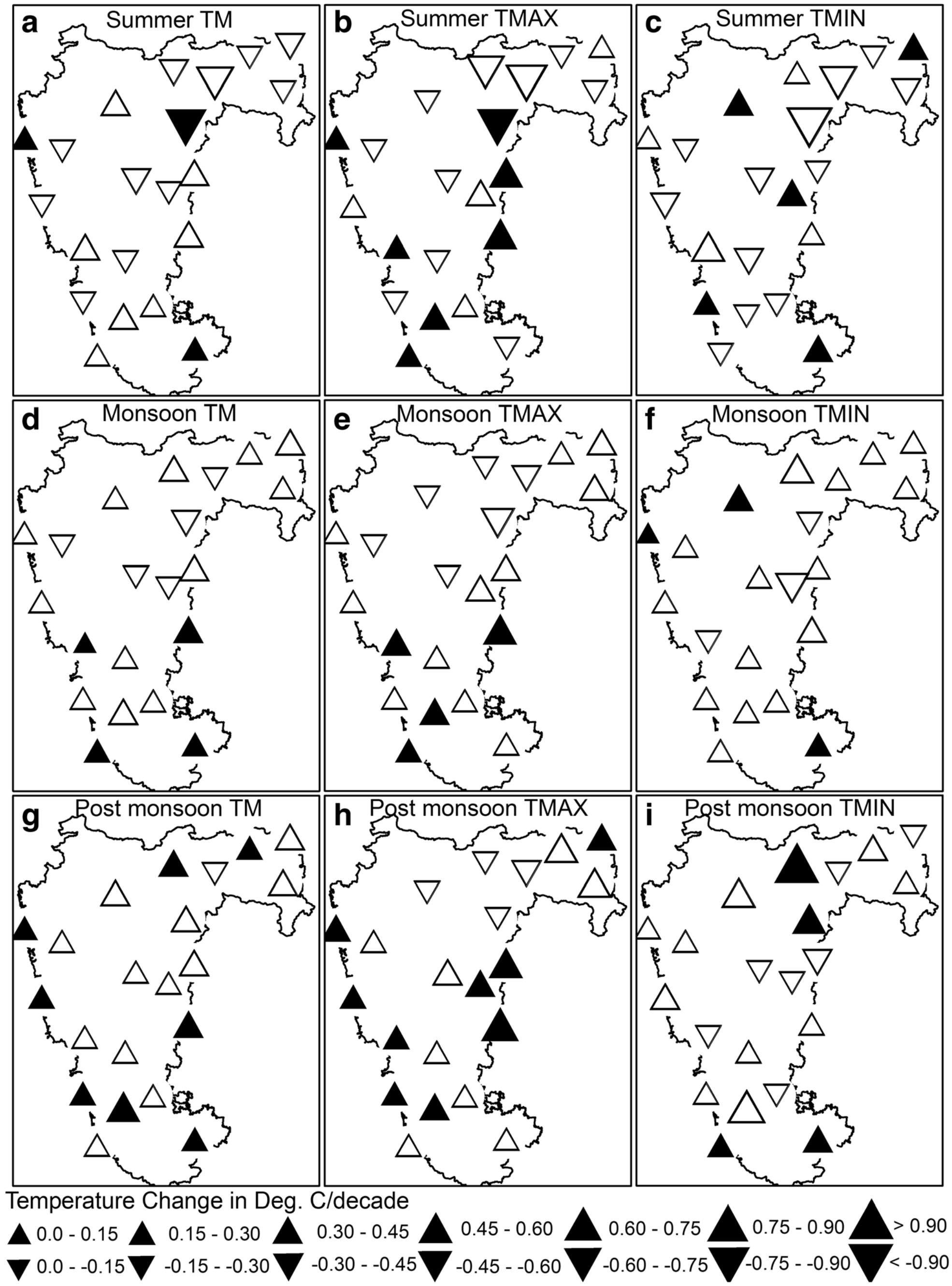
3.2 Trend analysis: comparison between linear regression, Sen's slope estimator, and MK test results

Figure 5 shows the comparison between linear regression, Sen's slope estimator, and MK test with respect to number of stations recording statistically significant trends. Overall percentages of positive significant stations were almost similar according to all the tests. But, a higher number of significant negative trends were detected by MK test and Sen's slope estimator. Annual TM and winter TMAX showed highest (61.9 %) stations recording positive significant trends according to the linear regression test; however, equal percentage of stations were registered for winter TMAX by both Sen's slope estimator and MK test. Results of all the tests are more or less similar for TM, TMIN, and TMAX. Overall, the results indicate that rising temperature trends dominate over the study area.

3.3 Cold and heat waves

Heat and cold waves are well-known extreme weather phenomena which cause enormous losses in terms of human discomfort, ailments arising, and lives lost. Heat and cold waves lead to sudden temperature changes in a short time span making it very difficult for human society to adjust with such a sudden variation. Heat waves are observed during March to June and cold waves during November to February; therefore, particular months were analyzed to assess heat and cold waves. The analysis focused on the number of days recording heat/cold wave conditions. Based on criteria mentioned by IMD, heat and cold waves were classified in three categories: slight, moderate, and severe. Criteria are different for stations with normal (mean) temperature below 40 °C and for stations with normal temperature above 40 °C (Table 1). Fig. 6a–c depicts distribution and decadal occurrences of cold waves. According to De et al. (2005), "cold waves mainly affect the areas to the north of 20 °N but in association with large amplitude troughs, cold wave conditions are sometimes reported from States like Maharashtra and Karnataka as well." Occurrence of slight cold wave varies over the study area. Some places showed increase in cold waves while some

Fig. 4 Trends (in degrees Celsius per decade) in summer (**a–c**), monsoon (**d–f**), and post monsoon (**g–i**) temperature significant at 95 % confidence level. *Filled triangles* indicate significant trends and *hollow triangles* indicate insignificant trends



stations experienced decreasing trends. Around 50 % of stations showed clear decreasing trends in occurrences of slight cold wave conditions. Thirty-three percent of stations recorded increasing trend and the remaining stations indicated no changes (Fig. 6a). Occurrences of heat and cold waves are more in the slight category followed by moderate and severe (Table 3). There were no clear spatial and temporal trends in occurrence of moderate cold waves. Pune station indicated constant reduction in occurrences of moderate and severe cold waves (Fig. 6b, c). Weather stations located in the north of the study area like Aurangabad, Akola, and Nanded registered a sudden decrease in moderate and severe cold wave frequencies. Almost all southern areas belonging to Karnataka state showed very few occurrences of moderate and severe cold waves. Decrease in the number of days with cold wave conditions indicates that the winters are warming. In the recent period from 1999 to 2006, Gulbarga and to some extent Gondia station confirms a noticeable increase in occurrences of cold waves than the previous three decades. In general, it can be inferred from Fig. 6a–c that particularly some eastern stations such as Gondia,

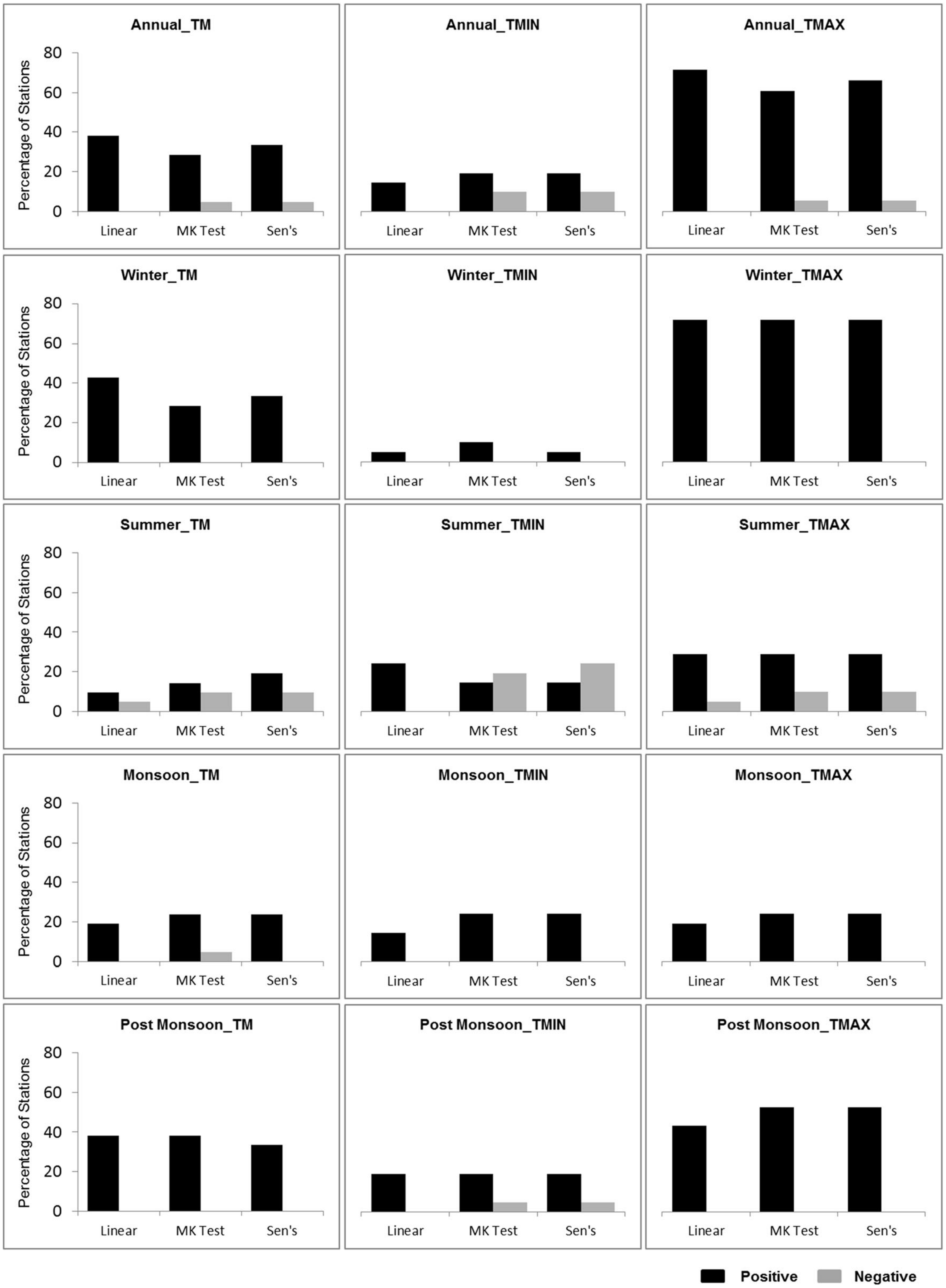


Fig. 5 Percentage of stations with significant trends in temperature obtained by linear regression, MK test and Sen's slope estimator

Gadchiroli, Gulbarga, and Chitradurg indicated an increase in the number of days with slight and moderate cold waves. Thus, mixed trends in occurrences of cold waves were observed over the area, but after 1978 there is a definite decrease in occurrences of cold waves of all categories. Increase in number of days with cold wave conditions at few interior locations is a matter of further study.

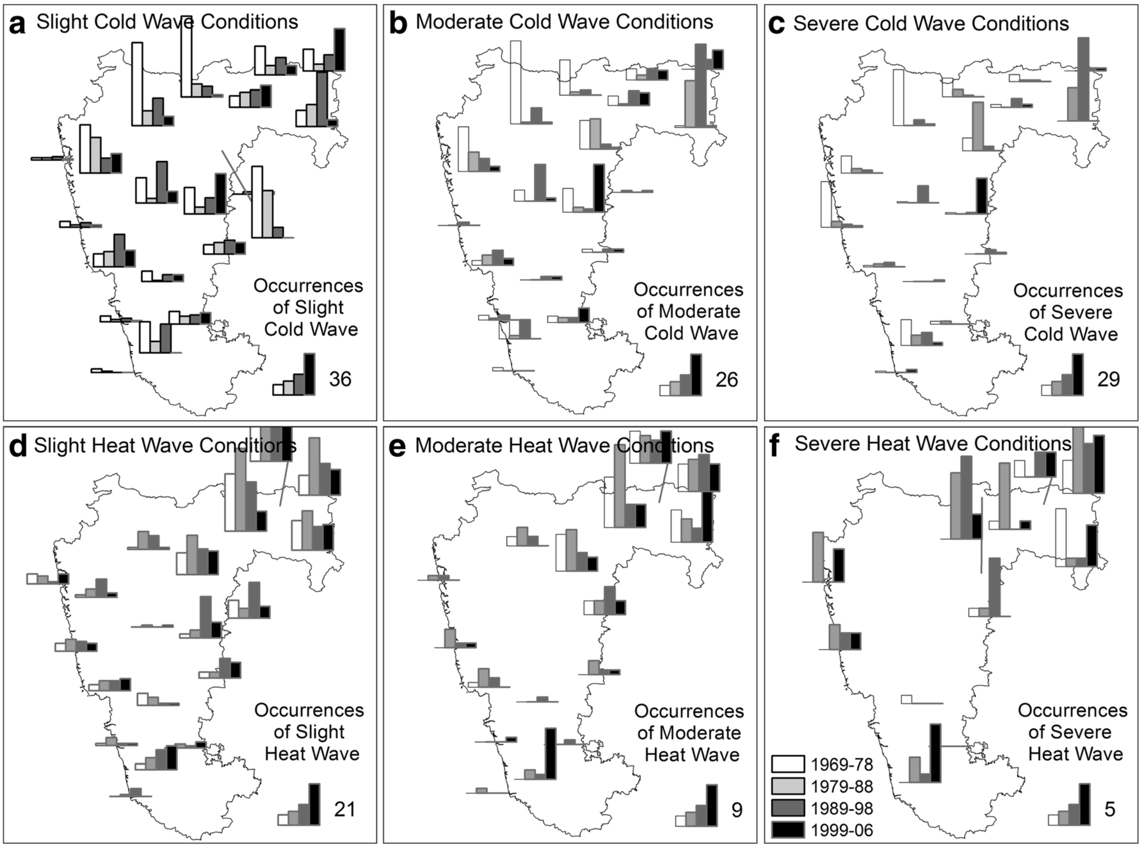


Fig. 6 Decadal changes in cold (**a–c**) and heat (**d–f**) waves over the study area

Figure 6d–f illustrates the occurrences of heat waves and their distribution over space and time. It can be inferred from the figure that the northeastern area experiences higher occurrences of heat waves than the other regions. Traditionally, this area is more affected by heat waves. The central part of the study area is almost a heat wave-free region. Shimoga, Gadchiroli, Gondia, and Nagpur weather stations showed increase in occurrences of heat waves in the recent period; Shimoga is located in the southern parts of the study area while the remaining stations belong to the northeast region. The coastal region registered very few heat waves during the study period, for example at Mumbai and Ratnagiri. Honavar and Mangalore recorded few slight (Fig. 6d) and moderate (Fig. 6e) heat waves while there is no record of severe (Fig. 6f) heat wave. In general, the occurrences of slight and moderate heat waves increased gently over the study period which is a sign of rising temperatures over the study area. The decade of 1979–88 showed the highest occurrences of heat waves (Table 3).

3.4 Spatio-temporal trends in temperature extremes

Widespread warming was observed over India by Kothawale et al. (2010), through increase in intensity and frequency of hot events and by Revadekar et al. (2012) with decrease in frequency of cold events. This study concentrated on finding the changes in hot and cold extremes based on percentiles over Maharashtra and Karnataka state of India. As mentioned in methodology, daily maximum/minimum temperature was used to find extreme hot/cold days/nights based on percentile and were classified into three classes for summer and winter

Table 3 Category-wise number of occurrences of heat and cold waves

Decades	Average no. of cold wave occurrences			Average no. of heat wave occurrences		
	Slight	Moderate	Severe	Slight	Moderate	Severe
1969–78	22	9	7	7	2	1
1979–88	10	4	4	10	4	2
1989–98	14	8	5	10	3	2
1999–06	9	4	2	6	2	2

season. This was done on the basis of indices identified and explained in Table 2.

3.4.1 Summer

Extremely hot days increased over the southern parts, whereas decreasing tendencies were observed over the northern region (Fig. 7a–c). Around 30 % of stations registered decreasing trends in extremely hot days and the remaining 70 % of stations recorded increasing trends (Fig. 7a). Very hot days increased at the rate of about 3 days per decade in the southern region and the rate constantly decreased northward (Fig. 7b). Around 38 % of stations showed decreasing tendency in very hot days and 62 % of stations recorded a rising trend. Similar pattern with different rates was observed in hot days. About 43 % of northern stations indicated decreasing trend in number of hot days. Four southern stations namely Bengaluru, Mangalore, Shimoga, and Chitradurga recorded increase in hot days ranging from 2 to 3 days/decade (Fig. 7c). In summary, it can be said that the days with higher temperatures are increasing over most of the study area.

Minimum temperatures below 5th/10th/15th percentile value have been considered as very cold nights/cold nights/moderate cold nights. Figure 7d–f illustrates the decadal change in cold extremes over different locations. Very cold nights have increased over the central parts of the study area with rates of about 2 days/decade, while both towards the north and south they have decreased (Fig. 7d). Gulbarga registered the highest increasing trend of very cold nights which was about 2 days/decade. Around 40 % of stations showed a negative trend in very cold nights. Aurangabad revealed the highest decreasing rate followed by Akola, Bidar, Bengaluru, and Nagpur. Figure 7e, f shows three concentrated pockets of increasing cold nights. Highest rate of increase is located in the central parts of the study area around Gulbarga and Solapur. The southern cluster is located around Mangalore and Shimoga whereas the northeastern cluster formed around Gadchiroli, Yavatmal, and Gondia. Cold nights decreased rapidly over Bengaluru with a rate of 2 days per decade. About 25 % of stations registered a rate of less than 1 day per decade increase in cold nights while 33 % of stations showed negative trends. More or less similar trends were observed in moderate cold nights. The rates of increasing and decreasing moderate cold nights were between +1 to −1 night per decade. Relatively larger cities like Bengaluru, Aurangabad, and Nanded showed increase in minimum temperature over the study period, and therefore, there is decrease in moderate cold nights. Most discernible change noticed is increase in moderate cold nights over the northeastern region of the study area, around Gadchiroli, Gondia, and Yavatmal, which are relatively less urbanized and these are also the locations surrounded by dense natural vegetation. This is another aspect that can be taken up for detailed investigation in future studies.

3.4.2 Winter

Figure 7g–i illustrates spatio-temporal trends in hot extremes during the winter season over the study area. Only four stations, Akola, Yavatmal, Solapur, and Gadag, showed negative trends in extremely hot days, while the remaining 81 % indicated increasing trends over the study region. Mumbai, Pune, and Aurangabad industrial regions showed rapid positive change in extremely hot days (Fig. 7g). The entire study region recorded an increase in very hot days over the study period except Akola, Yavatmal, and Nanded stations (Fig. 7h). Maximum temperature in the winter season at Gulbarga increased over the study period; as a result, this station showed the highest (2 days/decade) increase in very hot days. Almost all stations in the south experienced more than 1 day/decade rise. Compared to other extreme indices, very hot days in winter showed the highest increase. About 29 % of stations recorded a decreasing trend in hot days, particularly those located in the northern center of the study area (Fig. 7i). The southern part of the study area and coastal strip experienced an increase in the number of hot days. Generally hot days over the coastal region have increased by 1 day/decade. The southern and northeastern parts of the study area recorded positive changes in the number of hot days.

Warm extremes were found to be increasing over the area, whereas cold extremes showed a decreasing trend. Akola and Aurangabad stations have experienced a decrease in very cold nights with a rate of up to 3 nights/decade. The entire northwestern region has experienced an increase in night temperature over the study period. The central and northeastern part of the study area showed an increase in very cold nights (Fig. 7j). Fifty-seven percent of stations indicated a negative trend in very cold nights. However, very cold nights have increased at the rate of 2 nights/decade at Bidar. Cold nights have increased only around the central part of the study area with a rate of about 1 night/decade. On the other hand, they have decreased rapidly over the northern and southern parts with a rate of about five nights per decade. Results indicated that the cold nights decreased over 48 % of stations particularly located in the northern and southern parts of the study area (Fig. 7k). Among all cold extremes, moderate cold nights during winter had the highest rate of decrease, about five nights/decade. More than 71 % of stations showed a decreasing trend in moderate cold nights, whereas only a few stations indicated an increase in moderate cold nights (Fig. 7l). Thus, this parameter also indicates night-time warming over majority of the study area.

3.4.3 Comparison of cold and hot extremes

Comparison of trends in cold (hot) extremes during winter and summer seasons is illustrated in Fig. 8a, b. Trends in all cold extremes observed at each station during winter and summer

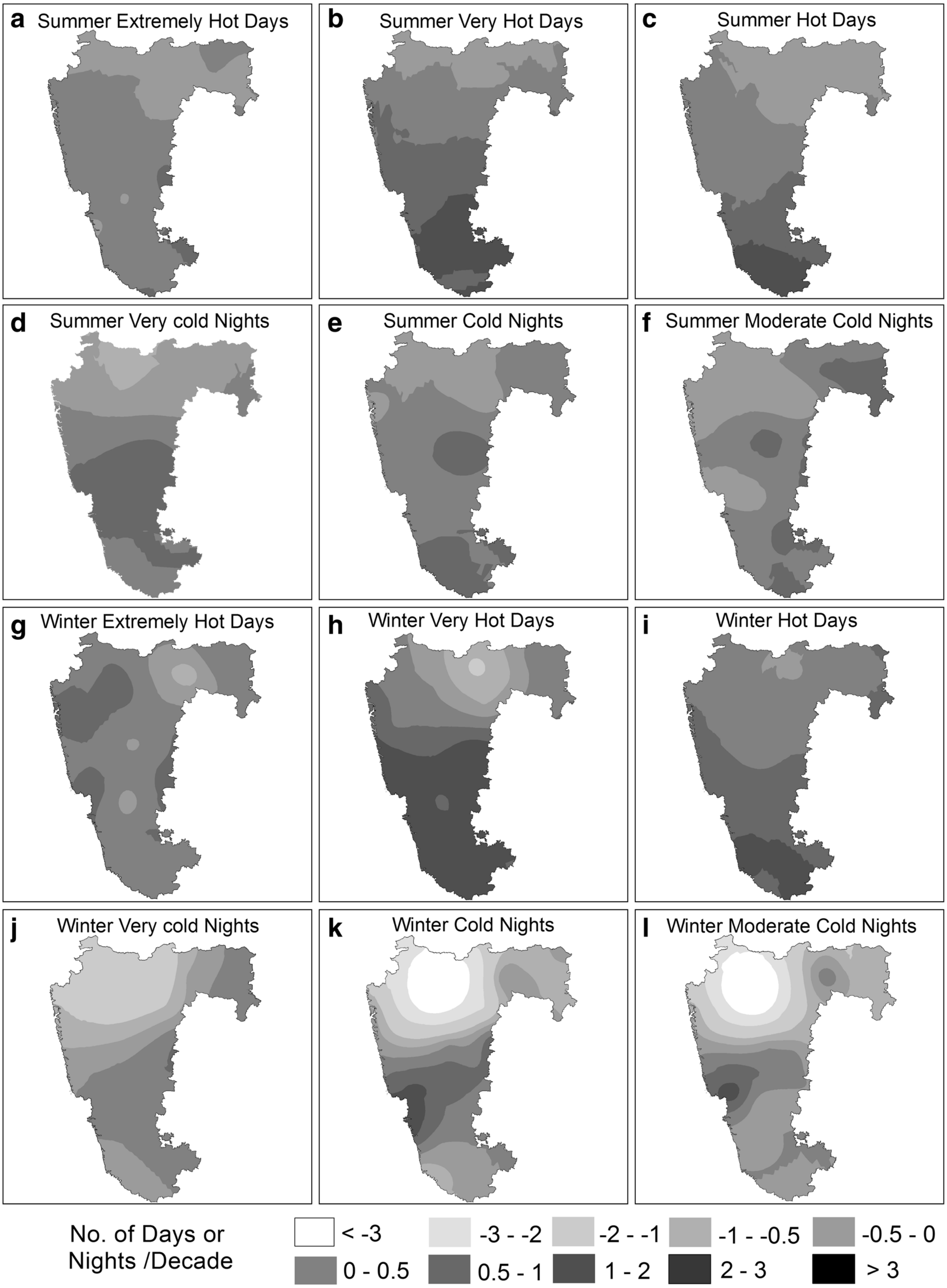


Fig. 7 Spatial distribution of decadal trends of hot extremes (**a–c**) and cold extremes (**d–f**) during summer and hot extremes (**g–i**) and cold extremes (**j–l**) during winter

are depicted in Fig. 8a. A close observation of the map indicates that the northern part of the area is dominated by a decrease in cold nights and the southern part by an increase in cold nights during winter. Another interesting aspect is the sweeping trends of increasing very cold nights during summer over the southern part, with the only exception of Belgaum

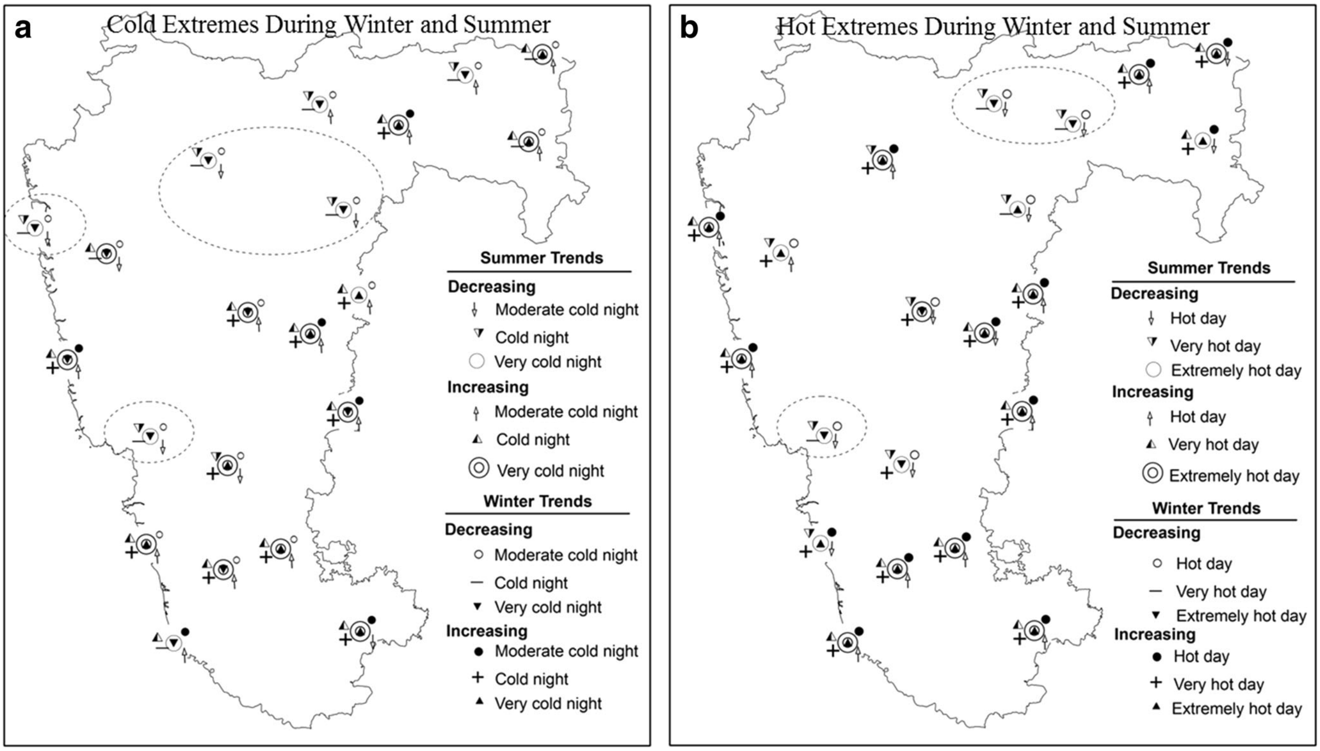


Fig. 8 Comparison of trends in cold extremes (**a**) and hot extremes (**b**) during winter and summer seasons. Stations recording decreasing trends in all extremes are *enclosed in circle*

and Mangalore. Moderate cold nights and cold nights during summer are also increasing at majority of the southern locations. This reveals that summer nights over the southern part are becoming colder. With respect to moderate cold nights, the northeastern part also shows a rising trend during summer. Thus, southern and northeastern areas depict similar tendencies in summer nights. Few stations registered decreasing trends in all the parameters, these are Aurangabad, Nanded, Mumbai, and Belgaum. Overall, it was observed that more than 70 % of stations showed a similar pattern of trends in cold and very cold extremes during both the seasons.

Map of hot extremes (Fig. 8b) indicates that the southernmost part of the study area experienced rising trends in extremely hot days, very hot days, and hot days during both summer and winter seasons. North of this area, similar trends are observed in the central eastern region, comprising the stations of Raichur, Gulbarga, and Bidar. When compared with cold extremes (Fig. 8a), it is evident that during winter, over these areas, days are getting warmer and nights colder. This is indicative of increasing range in day and night temperatures. Increasing trends in the western part are observed at Mumbai and Ratnagiri. Overall rising trends are observed in the northeastern part of the study area, represented by Nagpur, Gondia, and Gadchiroli stations. Thus, three areas of overall increasing tendencies can be identified, which are the southernmost region, east central region, and northeastern region. Three stations, Akola, Yavatmal, and Belgaum registered decreasing trends in all hot extremes in both the seasons. Detailed investigation of the trends revealed that with increase in the intensity of hot extremes, the number of stations with increasing trend in both the seasons increases along with the fall in the stations of decreasing trends.

4 Conclusion

The tropical location of Maharashtra and Karnataka states exposes them to higher temperatures with summers making the heat unbearable over most of the area. Little respite is brought by the sea breeze at coastal locations. Any rise in temperatures would make the conditions difficult for the inhabitants of the area. Such changes can occur with different intensities during different seasons. The present study attempted to investigate such changes in recent decades over these two states. The analysis revealed various aspects of climate variability over the area. It was observed that the annual TM over Maharashtra and Karnataka as a whole increased by about 0.44 °C, significant at 0.01 level. Seasonally, the increase in winter TM was about 0.76 °C (significant at 0.01 level); increase in post-monsoon TM was 0.86 °C, which was highest among seasons with respect to TM. Summer and monsoon TM did not register significant trends. Thus, post-monsoon and winter seasons which bring in cooler conditions showed signs of warming. This also indicates that if the rising trends continue in the near future, temperatures during these two seasons would be significantly higher than the temperatures experienced a few decades back. Further, the day-time temperatures (TMAX) during winter showed significant increase at 62 % of locations. Also, TMAX increased more rapidly than TMIN during winter. Extension of such trends in the future would lead to conditions where day-time temperatures during winter would be considerably higher than the decades of the late twentieth century. Since more number of stations from Karnataka recorded increasing trends, it can also be concluded that Karnataka is warming rapidly than Maharashtra.

Tendencies in some climate extremes are also indicative of climate variability. Analysis of the occurrences of heat and cold waves revealed some interesting aspects of their spatio-temporal variability. Nearly 50 % of stations registered a decrease in slight cold waves. Very few moderate cold waves were observed over the coastal region. Moderate and severe heat waves did not show any defined pattern. Occurrences of severe heat waves were not very frequent at majority of the stations; they were more frequent in the eastern region, particularly the northeastern part of the study area, which recorded a higher number of heat waves during the study period. Overall, the number of days with heat wave conditions increased slowly over the study area. Decreasing cold wave conditions and slow increase in heat waves is indicative of rising temperatures over the study area.

Considerable change is also noticed in the tendencies of indices based on percentiles. Extremely hot days have increased over the southern parts of the study area, while the northern part, particularly belonging to Maharashtra, showed a decrease in extremely hot days in the summer season. Analysis of cold extremes during summer revealed that there are three small clusters where moderate cold nights have increased, one around Gadchiroli, second around Solapur, and third around Chitradurg. The remaining area shows a decrease in cold extremes during summer, indicative of warming summer nights over large parts of these two states. During winter, an increase was observed in the hot extremes over the southern region and a decreasing trend was established over the northern parts of the study area. Compared to the increasing rate of cold extremes, the rate of decrease in cold extremes is higher over most of the study region. This undoubtedly indicates warming over the study area.

The analysis has provided more details of climate variability over the states of Maharashtra and Karnataka during recent decades with respect to temperature extremes. Though majority of the area has been subjected to rise in temperature and increasing trends of temperature extremes, it is difficult to make a sweeping statement about warming of this area. This is because some areas have also registered declining trends in hot extremes and rising trends in cold extremes. Thus, the research also opens up scope for further detailed investigation of some locations. However, the results obtained are indicative of spatial and temporal changes in annual and seasonal temperature, heat and cold waves, and temperature extremes over Maharashtra and Karnataka. Increasing trends in temperature and temperature extremes is not a good sign for these two states since a large part of these two states is subjected to frequent droughts, and further increase in hot temperature extremes would aggravate the problem for society in general.

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