Chapter 2
Variability and Long-Term Changes in Surface Air Temperatures Over the Indian Subcontinent

A.K. Srivastava, D.R. Kothawale and M.N. Rajeevan

1 Introduction

Surface air temperature is one of the most important meteorological parameters of the climate system. It is widely used to detect the first signal of climate change. The term, "global warming," frequently discussed today, is a consequence of the substantial rise in surface temperatures across the globe. With the steep rise in surface temperatures over the past few decades, global warming is being viewed as a triggering source of the observed and projected rise in the frequency and intensity of many extreme weather events. Owing to this observed and projected temperature rise, climate models indicate larger changes in the climate system, on regional and planetary scales. Probable changes in the climate systems affecting the Indian subcontinent, due to rise in regional surface temperatures, are of great concern. Changes in seasonal temperatures over the region, especially trends in temperature gradients, may induce a significant change in monsoon performance and its effect on crop production. Hence, it is desirable that a true assessment of the rise in the surface temperatures over the Indian subcontinent is carried out. In this chapter, we document the past observed changes in surface air temperatures over the region as a whole and on different parts of the region. The analysis has been done for (a) for the whole data period 1901–2010 and (b) recent 30 years 1981–2010.

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2 Review of Past Work Done

Past studies reported that the global as well as regional mean surface air temperatures have increased significantly in the last century (Jones and Moberg 2003). The rise has been steep and more pronounced in the recent decades (IPCC-AR4 2007; IPCC-AR5 2014, and the references therein). With the availability of sufficiently long instrumental temperature records, attempts to investigate temporal variations of temperatures over India were made in as early as in the 1950s. Pramanik and Jagannathan (1954) examined the trends of maximum and minimum temperatures of 30 Indian stations for the period 1880–1950 to conclude that generally there was no significant trend in maximum and minimum temperatures. In one of the earliest studies in the context of contemporary global warming, Hingane et al. (1985) reported that the mean annual temperature has increased by about 0.4 °C/100 years in India during the period 1901–1982. Srivastava et al. (1992) studied decadal trends in the climatic parameters over India for the 1901–1986 period. The study highlighted that there was in general, a widespread cooling over northern India and warming over southern India. Rupa Kumar et al. (1994) pointed out that the increase in annual mean temperatures over India during 1901–87 was mainly contributed by the increase in maximum temperatures with the minimum temperatures remaining practically trendless. After filtering out the global effects of greenhouse gases and natural variability, Krishnan and Ramanathan (2002) found that all India surface air temperature during the drier part of the year (January–May) cooled by as much as 0.3 °C since 1971. Subsequent analysis by Kothawale and Rupa Kumar (2005) brought out that both the all India annual maximum and minimum temperatures rose significantly during the 1971–2003 period. Kothawale et al. (2010) examined the temperature data of the period 1901–2007 to conclude that there was significant rise in all India mean, maximum, and minimum temperatures, and pace of the warming was more in recent years. Recently, Kothawale et al. (2012) examined the spatial and temporal asymmetry of temperature trends over India and the possible role of aerosols. Thus, there are several studies which examined and highlighted temperature trends over India.

However, most of the above studies used temperature data of limited number of stations and did not use temperature data of all the stations for which temperature records are available in the archives of the India Meteorological Department (IMD). Moreover, above studies examined the trend in temperature over different time spans. Further, spatial variation of the temperatures was also not examined by most of the studies. Therefore, there is not only a need to assess actual rise in the temperature data over India using long series of temperature data of all the stations but also to examine the spatial variability. The present analysis aims to do the same by utilizing data of all the stations for which data are recorded, quality controlled, and archived.

2.1 Data and Methodology

For the present study, monthly maximum and minimum temperature data of 395 available stations for the period 1901–2010 were collected from the IMD archives. Figure 1 shows the spatial distribution of stations whose data were used in this study. The data were subjected to basic quality checks such as rejecting values, greater than exceeding known extreme values, minimum temperature greater than the maximum temperature, and same temperature values for many consecutive days. Unusual high values were flagged by putting a filter suggested by Sellers and Liu (1988). The flagged values showing spatial continuity were accepted and only the isolated values were rejected. Using station data, 1.0° × 1.0° gridded data for the Indian region were prepared. The development of data set was based on the methodology of Jones and Moberg (2003) and Srivastava et al. (2009) by interpolating anomaly series (based on 1961–1990 period). Monthly temperature series for the country (India) were computed by area-weighted average of the grid point data series.

Annual/seasonal, winter (January and February), premonsoon (March–May), monsoon (June–September), and postmonsoon (October–December) temperature

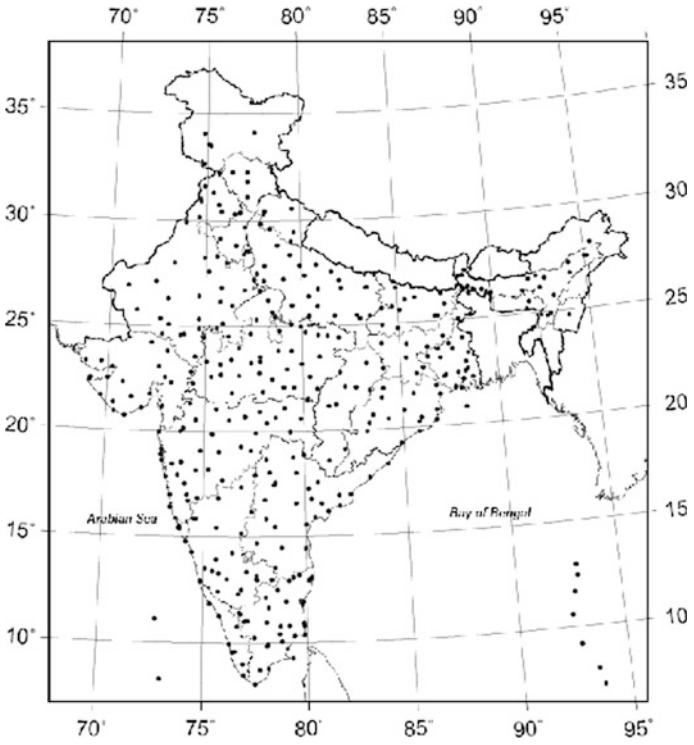


Fig. 1 Network of 395 stations selected for developing the gridded data set

series for the period 1901–2010 were constructed by taking arithmetic average of the months of the year/season. Temperature series were examined for long-term variations and trends for the 1901–2010 and 1981–2010 periods. The trend was estimated by fitting a simple linear regression to the time series. A trend in the annual temperature (maximum and minimum) series over different moving 30-year periods such as 1901–1930 and 1911–1940 was also examined. The statistical significance of a trend was assessed by testing significance of regression coefficients of the fitted lines in the different annual and seasonal temperature time series. In addition to the trend analysis, confidence intervals of the trends are also calculated.

3 Results and Discussions

3.1 Annual Trend of All India Temperatures

The all India annual mean, maximum, and minimum temperature series are shown in Fig. 2. A significant increasing trend of 0.6 °C per 100 years is observed in the all India annual mean temperatures for the period 1901–2010. It may be seen that the annual maximum temperature rose consistently over the data period and rate of increase is 1.0 °C per 100 years for the period 1901–2010. Similarly, in the annual minimum temperature series, a significant increasing trend of 0.18 °C per 100 years for the period 1901–2010 is noticed. We may observe that the minimum temperatures did not witness any significant rise over most of the data period except during the recent few decades. Therefore, the rise in annual mean temperatures is primarily contributed by the increase in maximum temperatures. These trends are statistically significant at the 95 % confidence level.

From Fig. 2, we may also observe that the rate of warming as 0.18 °C per decade. Thus, although maximum temperatures increased gradually and consistently over the entire period, the rate of rise during the past 30 years was almost double. It may also be seen that rise in minimum temperatures was very spectacular for the period 1981–2010 as annual minimum temperatures (which was practically trendless till 1980) increased at the rate of 0.17 °C per decade.

3.2 Seasonal Temperatures

Seasonal mean, maximum, and minimum temperature anomaly series and their trends are shown in Fig. 3a–d. During the period 1901–2010, there was a significant rise in the mean temperatures in all the seasons. Increase in the mean temperatures was the highest in the postmonsoon (0.79 °C per hundred years) and winter (0.70 °C per hundred years) seasons, followed by the premonsoon (0.55 °C per hundred years) season. The mean temperature during the monsoon season

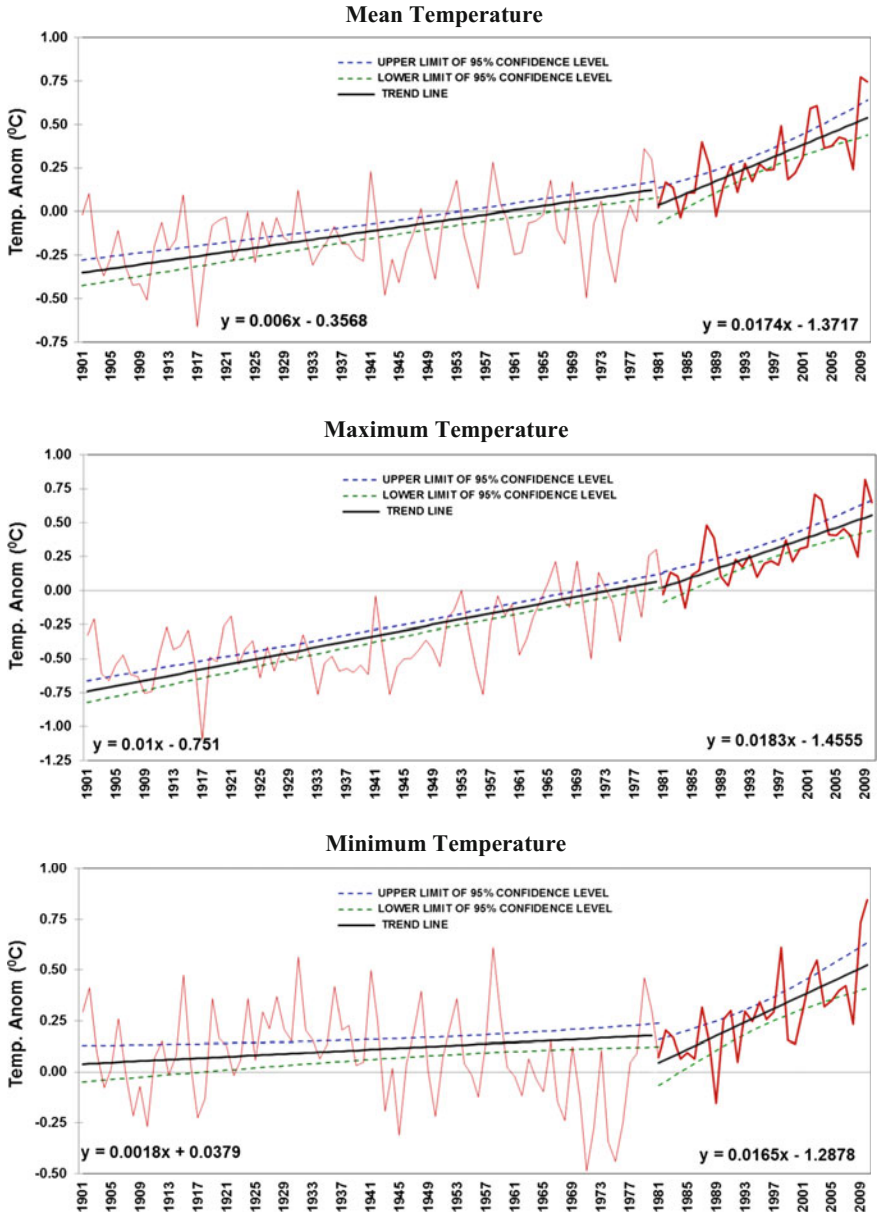


Fig. 2 All India annual mean, maximum, and minimum temperature anomaly series and the linear trends

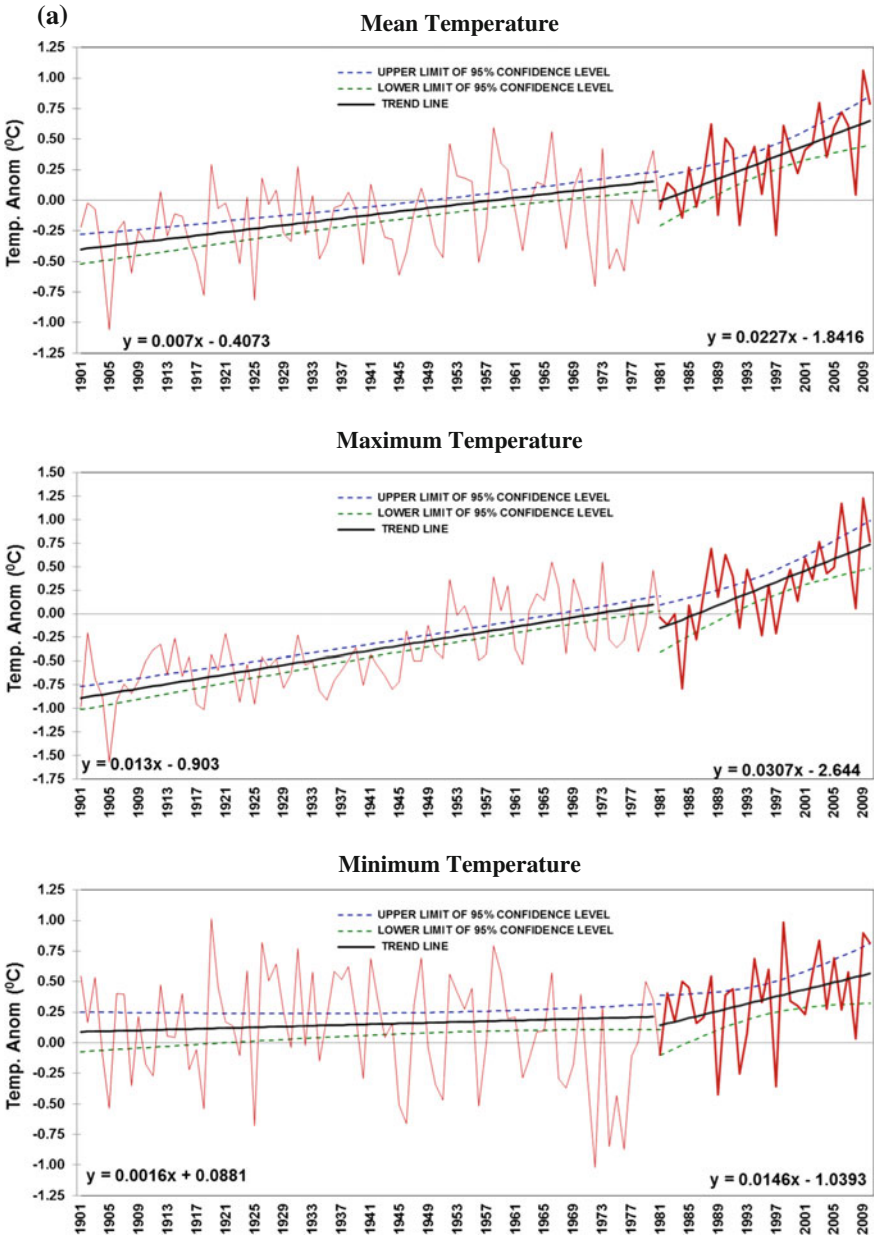
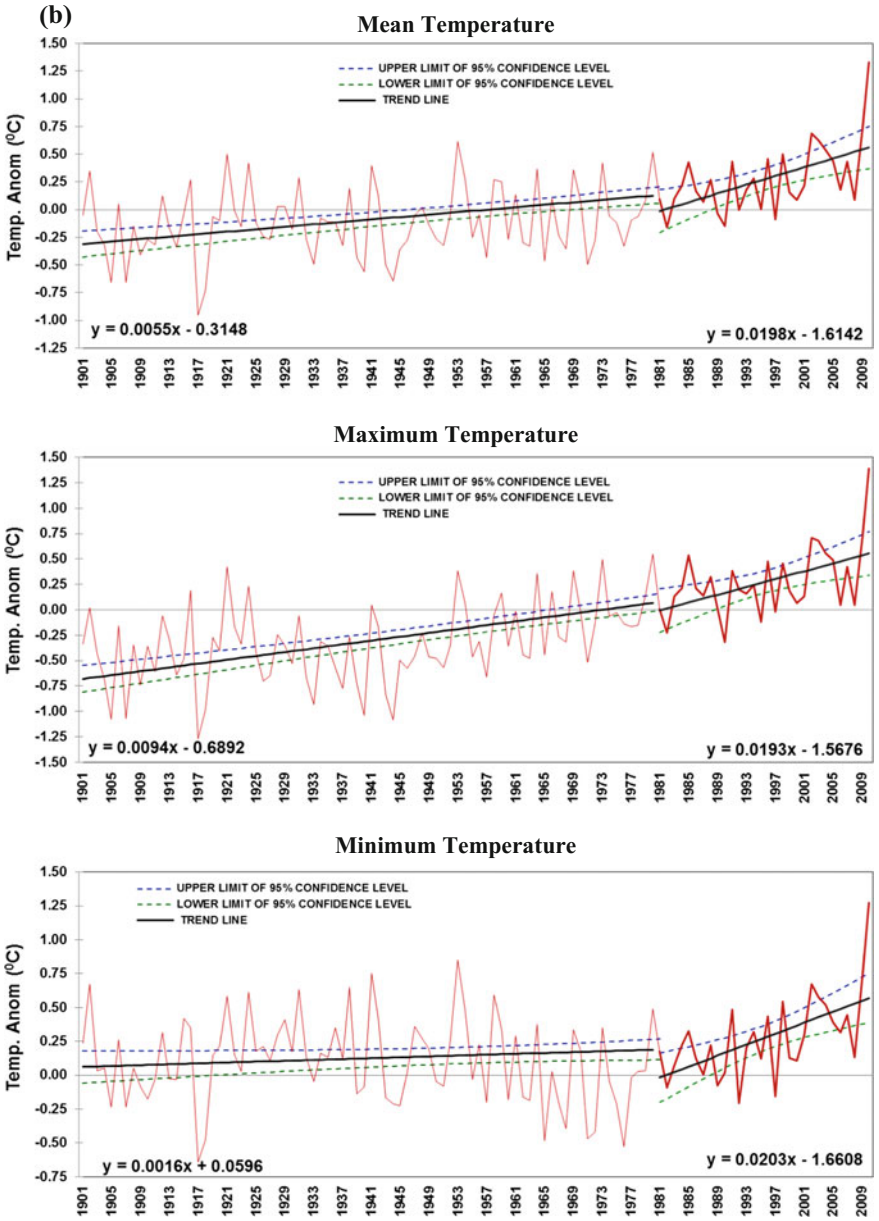


Fig. 3 **a** All India mean, maximum, and minimum temperature anomaly series and the linear trend for the winter season. **b** All India mean, maximum, and minimum temperature anomaly series and the linear trend for the premonsoon season. **c** All India mean, maximum, and minimum temperature anomaly series and the linear trend for the monsoon season. **d** All India mean, maximum, and minimum temperature anomaly series and the linear trend for the postmonsoon season



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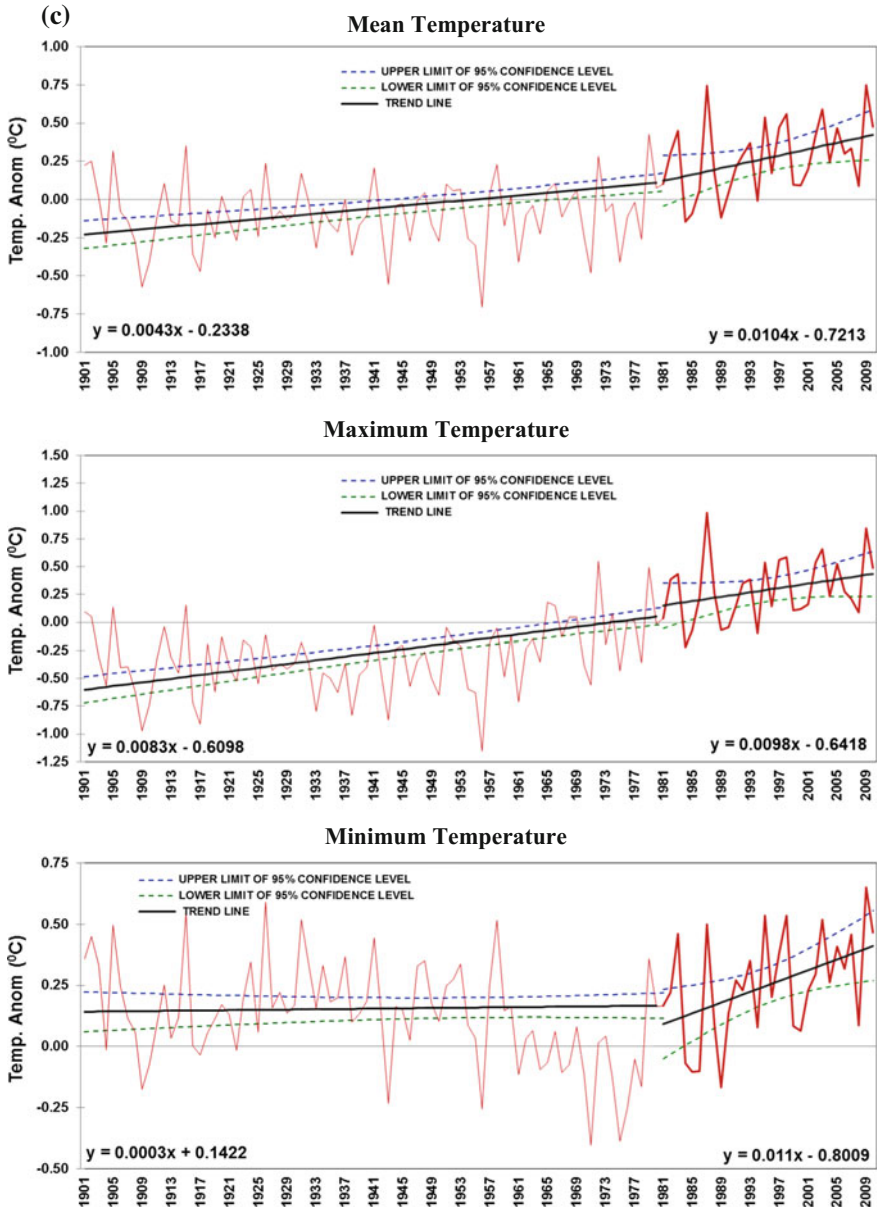

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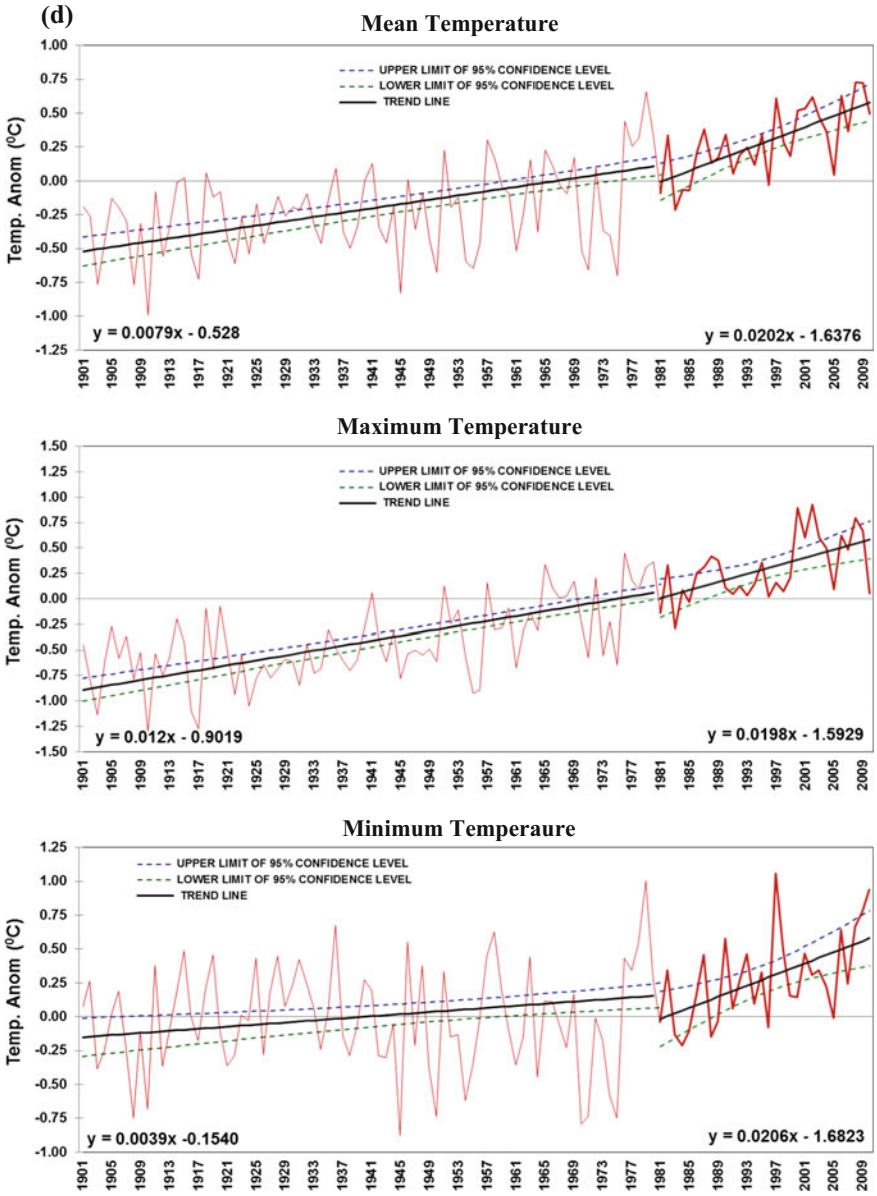

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Table 1 Surface air temperature trends for the country as a whole

Season	1901–2010			1981–2010		
	Mean temperature (°C) per 100 years	Maximum temperature (°C) per 100 years	Minimum temperature (°C) per 100 years	Mean temperature (°C) per decade	Maximum temperature (°C) per decade	Minimum temperature (°C) per decade
Annual	0.60	1.00	0.18	0.17	0.18	0.17
Winter (Jan–Feb)	0.70	1.30	0.16	0.22	0.31	0.15
Premonsoon (Mar–May)	0.55	0.94	0.16	0.20	0.19	0.20
Monsoon (Jun–Sep)	0.43	0.83	0.03	0.10	0.10	0.10
PostMonsoon (Oct–Dec)	0.79	1.20	0.39	0.20	0.20	0.20

showed the least rise of 0.43 °C per hundred years. Similarly, there is a significant rise in the maximum temperature in all the seasons and the rate of increase is also almost constant around 1.0 °C per 100 years, except during the monsoon season in which the rise was less than 1.0 °C per 100 years. The minimum temperatures were practically stationary (trendless till 1980) in all the seasons except the postmonsoon season during which significant rise was observed (0.39 °C per 100 years).

Further, during the recent three decades (1981–2010), the mean temperature rose significantly in all the seasons. The rate of rise in the mean temperature is about 0.2 °C per decade in all the seasons except the monsoon season during which an increase of 0.1 °C per decade was observed. Similarly, during the period, maximum temperature rose at about 0.3 °C per decade for the winter season and at 0.2 °C per decade for the pre- and postmonsoon seasons. The rise was the least at 0.1 °C per decade during the monsoon season. During the period, minimum temperatures also increased significantly in all the seasons and the rate of increase is the highest during the pre- and postmonsoon seasons (around 0.2 °C per decade). The rise in minimum temperature in the winter season during the period is around at 0.15 °C per decade, while the increase in the monsoon season during the period is the least (0.1 °C per decade). Trend values in the annual and seasonal temperatures are given in the Table 1.

3.3 Spatial Patterns of Temperature Trends

The spatial pattern of temperature trends in the annual/seasonal, mean, maximum, and minimum temperature series for the periods 1901–2010 and 1981–2010 was examined and its statistical significance was tested. Spatial patterns of the trend in the annual and all the four seasons in respect of mean, maximum, and minimum temperatures during the periods 1901–2010 and 1981–2010 are shown in Figs. 4 and 5a–d.

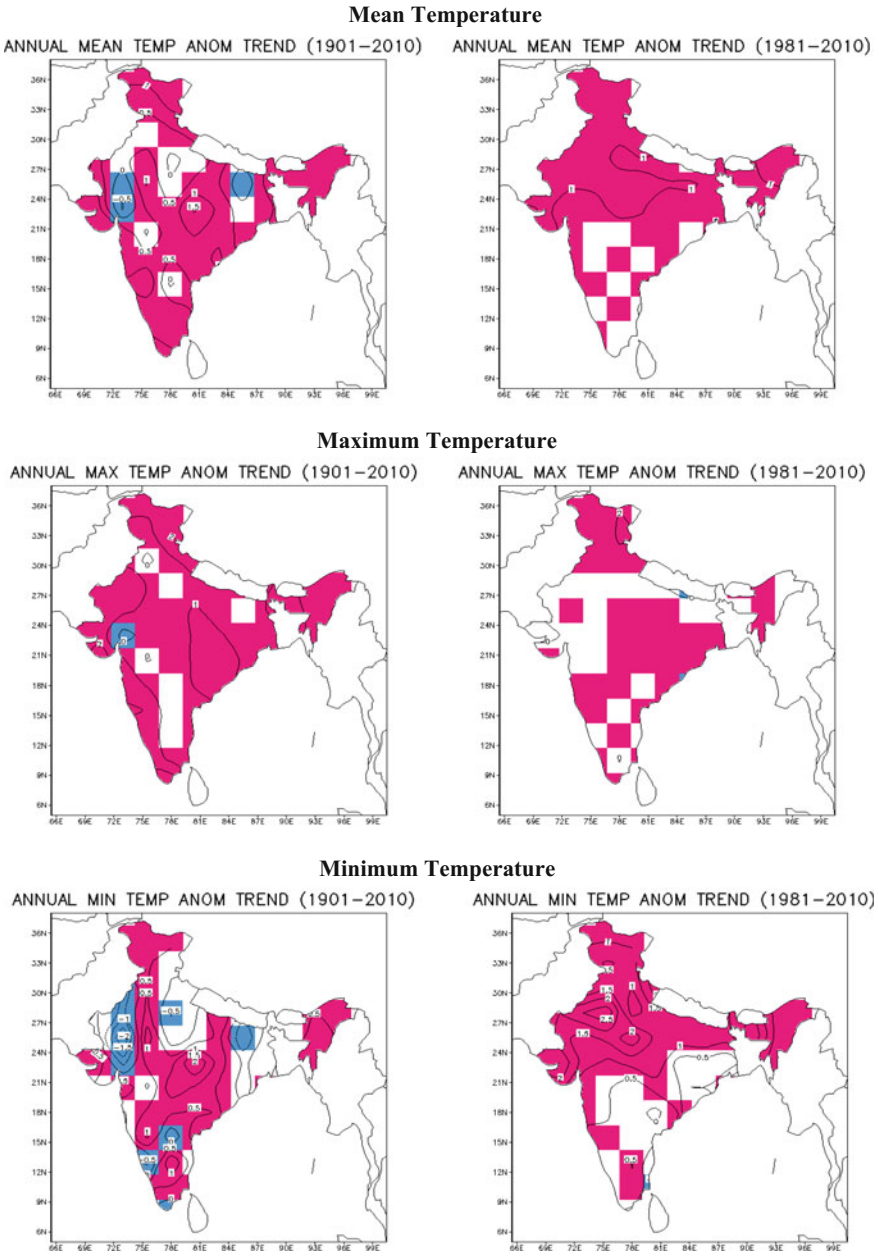
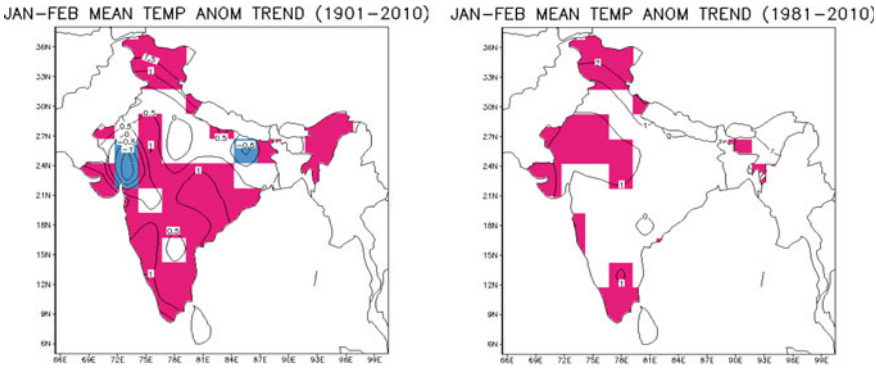


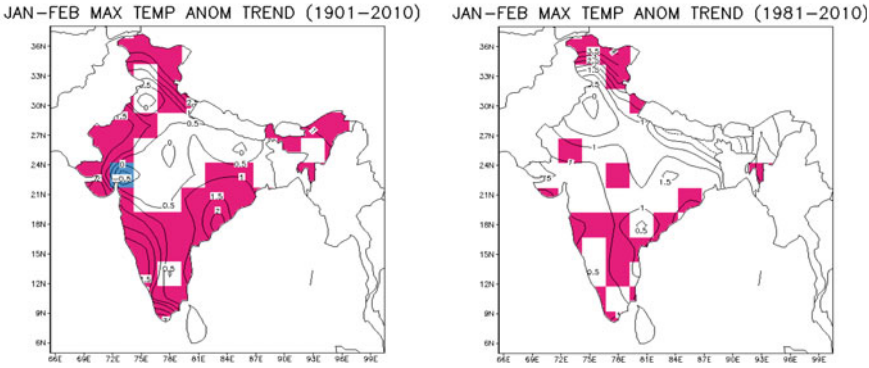
Fig. 4 Spatial pattern of the trend in annual mean, maximum, and minimum temperatures for the 1901–2010 and 1981–2010 periods. *Shaded regions* represent the regions where trends are significant at the 95 % confidence level. *Red* and *blue* regions show significant increase and decrease, respectively, and magnitude of trend during the periods is depicted by contour lines (color figure online)

(a)

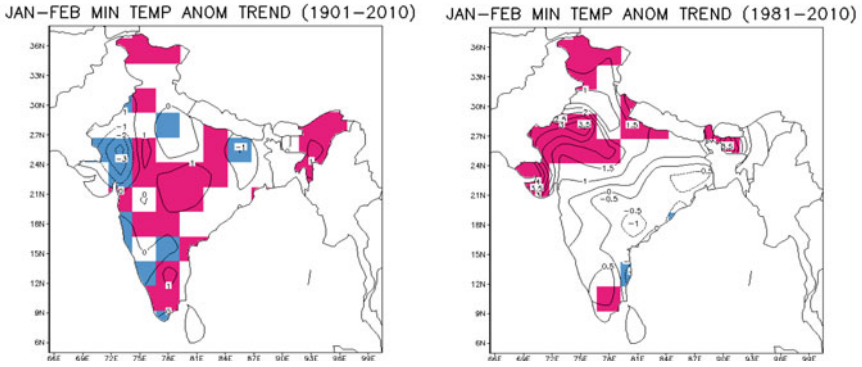
Mean Temperature



Maximum Temperature



Minimum Temperature



◄ **Fig. 5** **a** Spatial pattern of the trend in mean, maximum, and minimum temperatures during the postmonsoon season for the periods 1901–2010 (*left*) and 1981–2010 (*right*). *Shaded regions* represent the regions where trends are significant at the 95 % confidence level. Magnitude of total trends during the periods is depicted by *contour lines*. **b** Spatial pattern of the trend in mean, maximum, and minimum temperature during the winter season for the periods 1901–2010 (*left*) and 1981–2010 (*right*). *Shaded regions* represent the regions where trends are significant at the 95 % confidence level. Magnitude of total trends during the periods is depicted by *contour lines*. **c** Spatial pattern of the trend in mean, maximum, and minimum temperature during the premonsoon season for the periods 1901–2010 (*left*) and 1981–2010 (*right*). *Shaded regions* represent the regions where trends are significant at the 95 % confidence level. Magnitude of total trends during the periods is depicted by *contour lines*. **d** Spatial pattern of the trend in mean, maximum, and minimum temperatures during the monsoon season for the periods 1901–2010 (*left*) and 1981–2010 (*right*). *Shaded regions* represent the regions where trends are significant at the 95 % confidence level. Magnitude of total trends during the periods is depicted by *contour lines*

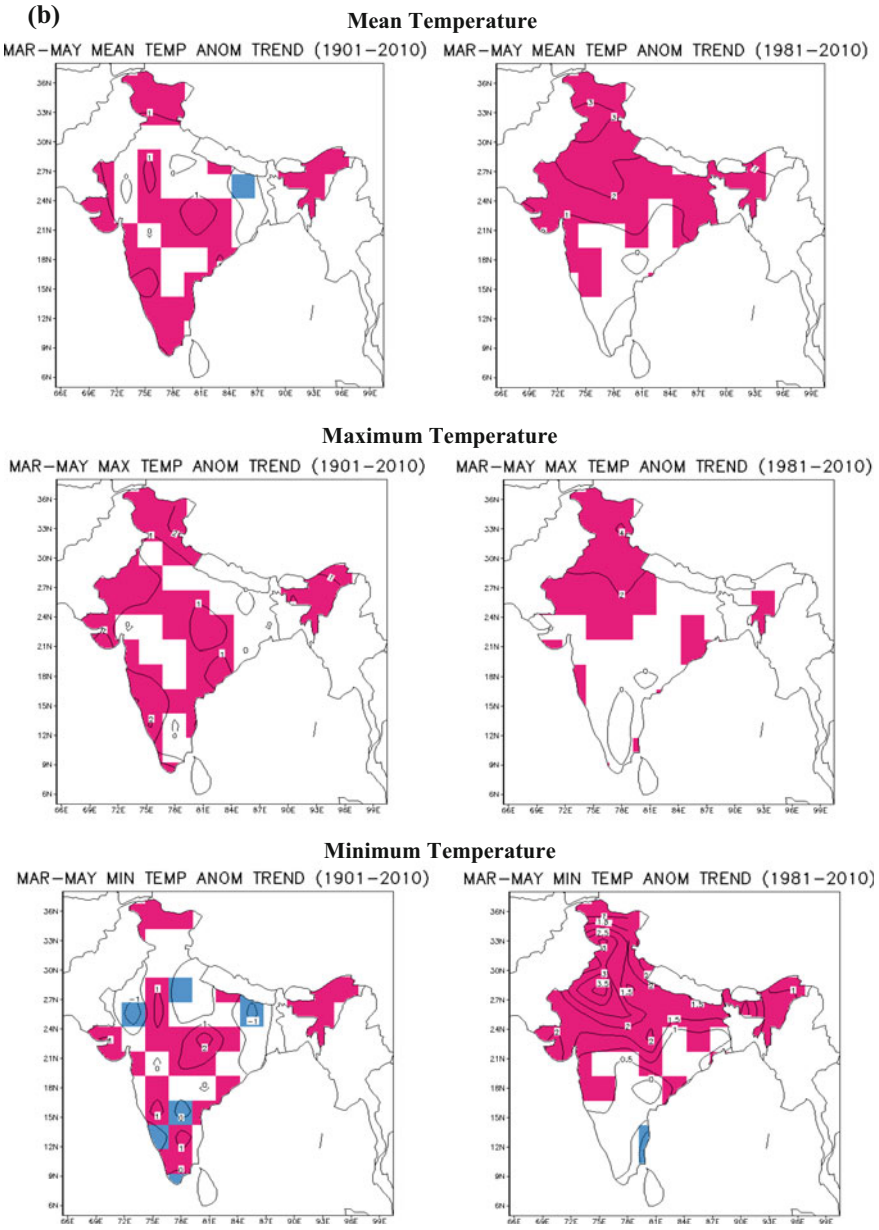
Annual Temperatures

During the 1901–2010 period, significant increasing trends in the annual mean temperature are observed over a large part of the country. However, significant negative trend is observed over northwestern parts of Central India (Fig. 4) and some isolated parts in the country. For the period, significant increasing trends in the annual maximum temperature are observed over almost the entire country. Similarly, the spatial pattern of trend in annual minimum temperatures data for the whole period exhibits a significant increasing trend over most parts of the Peninsular India and some northern, south-central regions of the country. Significant negative trends are also observed over parts of Gujarat, western Rajasthan, and some parts of the peninsula.

For the period 1981–2010, the spatial pattern of trend in the annual mean temperature suggests significant warming over most parts of the country except the Peninsular India. Similarly, in the annual maximum temperatures, a significant rising trend over parts of northern, east-central, and Peninsular India was also observed. During the period, significant rise in annual minimum temperatures was observed over most parts of the country except the peninsula.

Spatial Trends in the Seasonal Temperatures

For the period 1901–2010, significant increasing trend was observed in the spatial pattern of mean temperatures during the winter and postmonsoon seasons. However, warming was more widespread during the postmonsoon season. During the premonsoon and monsoon seasons, significant rise was limited to some parts of the Peninsular and Central India and the eastern region. Similarly, in the maximum temperatures, significant increasing trend was observed over most areas of the country during the postmonsoon season. In the winter, premonsoon, and monsoon seasons, significant rise was observed over the peninsular and northern parts, and



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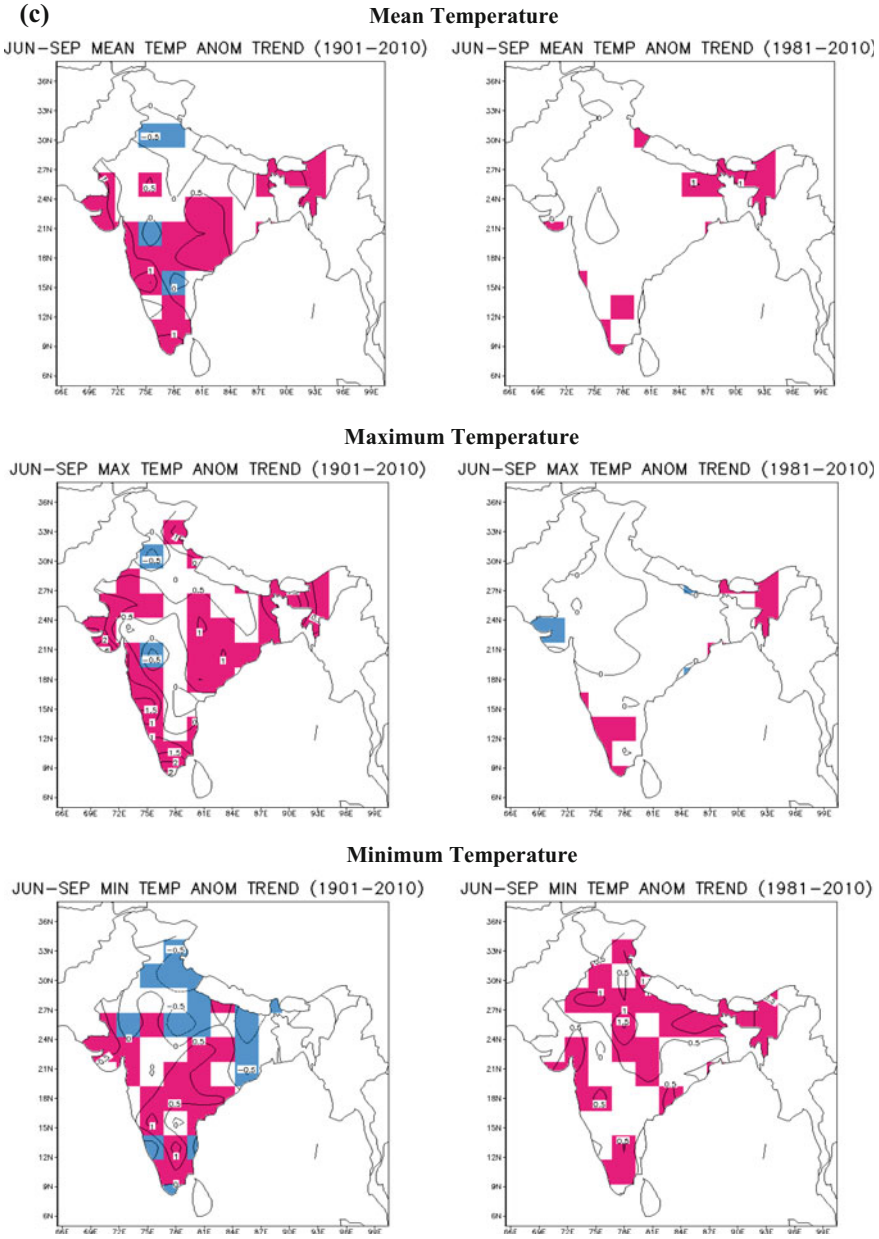

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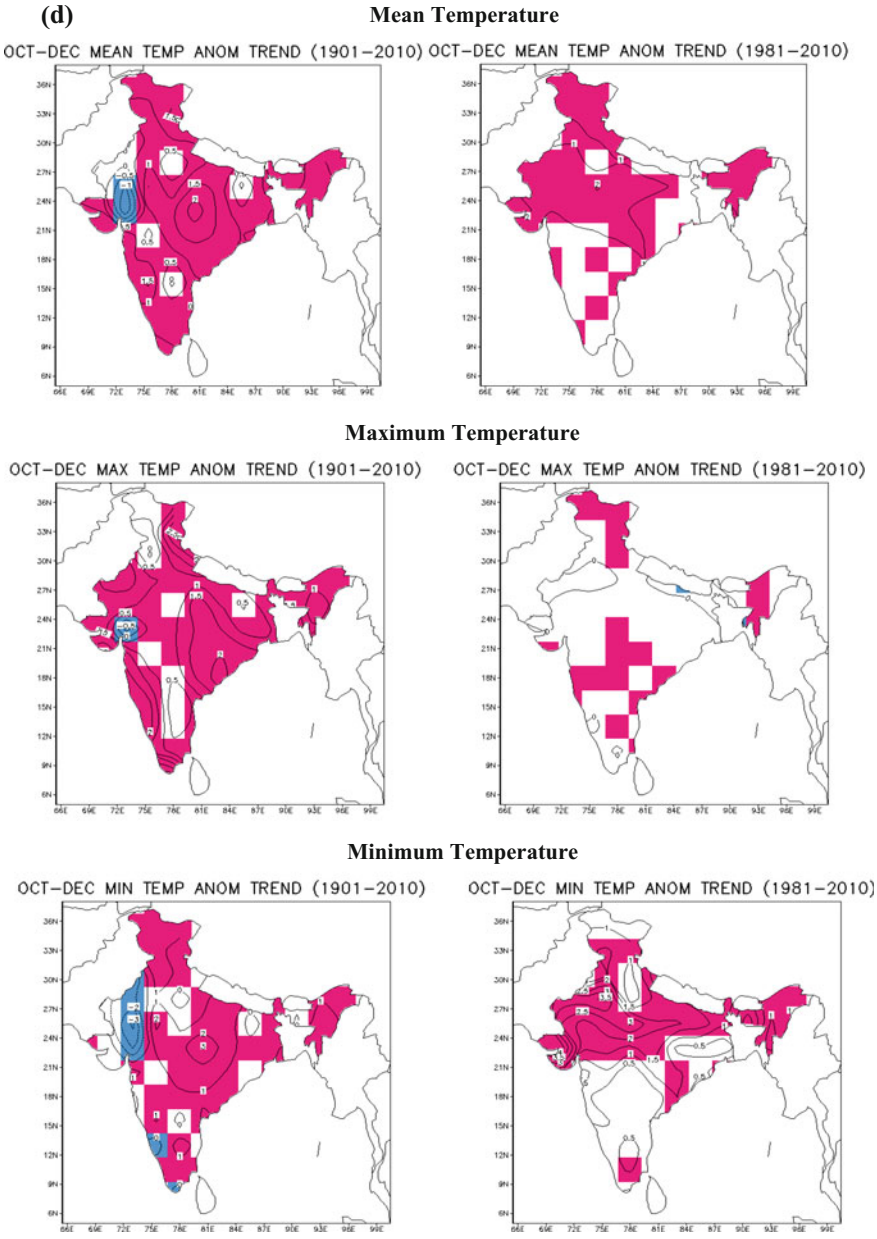

Fig. 5 (continued)

no significant trend was noticed over the central and adjoining parts. Spatial pattern of trend of the minimum temperature data for the whole period suggests a significant increasing trend over larger parts of the country (except some central and northwestern regions) in the postmonsoon season. In the other remaining seasons, rising trend was widespread over the peninsular parts and over some isolated regions.

For the period 1981–2010, spatial trend in mean temperatures showed a significant warming over most parts of the country (except Peninsular India) in the pre- and postmonsoon seasons. In the winter season, significant rise was limited to the northwestern, extreme northern, and peninsular parts, whereas during the monsoon season, no region witnessed any significant trend. Similarly, spatial pattern of trend in the maximum temperatures for the period 1981–2010 shows a significant rise over the extreme northern parts and Peninsular India. In the pre- and postmonsoon seasons, maximum temperatures witnessed significant increasing trend over most parts of northern India. Spatial pattern of trend in minimum temperatures for the period 1981–2010 exhibits significant rise over the northern, central, and northeastern parts during the pre- and postmonsoon seasons. Winter season witnessed significant increasing trend over parts of northwestern India and some isolated region, whereas significant rise was observed over some parts of the northern, central, and eastern regions of the country during the monsoon season.

4 Trend in Upper-Air Temperatures

In order to assess changes in the upper-air temperatures, the all India annual/seasonal tropospheric temperature series were computed by simple averaging of upper-air temperature data (for the year/season), recorded at RS/RW stations located in the country. Temperature data series of upper air, viz. 850, 700, 500, 200, and 150 hPa levels, for the period 1971–2007 were examined for assessing the trends, if any. The statistical significance of the trend was assessed by applying the Mann–Kendall rank test. The analysis suggests that the annual upper-air temperature averaged over the country as a whole showed a significant increasing trend at 850 and 700 hPa levels (Fig. 6). The annual temperature at the 500 hPa level also showed an increasing trend but the same was not statistically significant. Temperature data of other upper-air levels did not show any significant trend. On the seasonal scale, only for the winter season, significant increasing trend was observed for all the above three levels. During the pre- and postmonsoon seasons, an increasing trend (not significant) at the three levels, viz., 850, 700, and 500 hPa levels, was observed. There was no trend in the upper-air temperatures during the monsoon season.

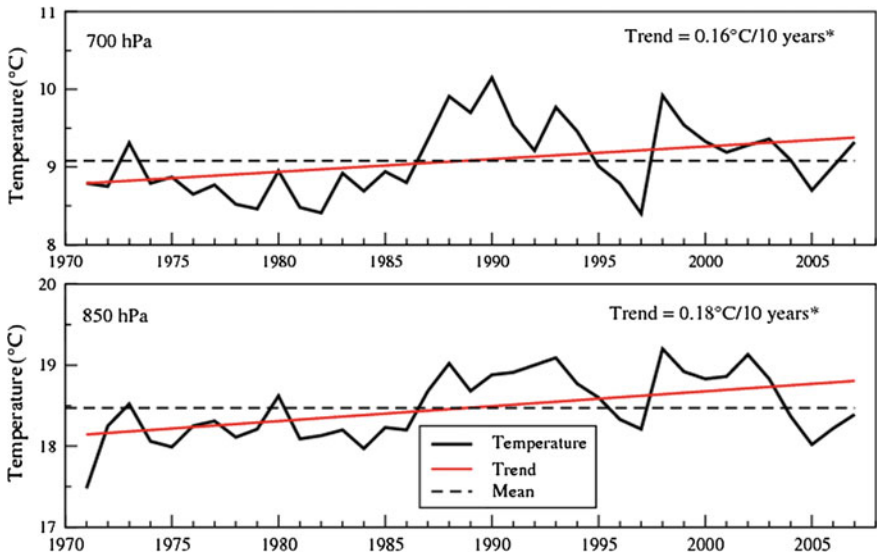

Fig. 6 All India annual upper-air temperature series and its linear trend at the 850 hPa (1.5 km) and 700 hPa (3.1 km) levels. The trends are significant at the 95 % confidence level

5 Summary

Annual mean and maximum temperatures for the country as a whole have increased significantly by around 0.6 and 1.0 °C per hundred years, respectively, during the period 1901–2010. Similarly, the annual minimum temperatures for the country as a whole increased by 0.18 °C per hundred years. On the seasonal scale also, mean and maximum temperatures for the country as a whole increased significantly in all the seasons, while only the postmonsoon season witnessed significant rise in respect of minimum temperatures.

Maximum temperature series exhibited an accelerated warming during the recent 30-year period (1981–2010). Minimum temperature series also witnessed a very rapid rise during the last thirty years, similar to that observed in maximum temperatures. Therefore, the rate of rise in the mean temperature for the country as a whole is almost three times as that of the same for the whole period (1901–2010). Most of the rise in maximum and minimum temperatures during the recent 30 years is more prominent over the northern, central, and eastern/northeastern parts of the country. Peninsular India witnessed the least warming during the recent 30-year period. Annual upper-air temperatures averaged over the country as a whole for the period 1971–2007 also showed a significant increasing trend at the 850 and 700 hPa levels. This suggests that the warming is not only confined on the surface, but also extends up to 3 km in the troposphere.

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