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Evaluation of temperature trends over India

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Abstract The impact of climate change is projected to have different effects within and between countries. Information about such change is required at global, regional and basin scales for a variety of purposes. An investigation was carried out to identify trends in temperature time series of 125 stations distributed over the whole of India. The non-parametric Mann-Kendall test was applied to detect monotonic trends in annual average and seasonal temperatures. Three variables related to temperature, viz. mean, mean maximum and mean minimum, were considered for analysis on both an annual and a seasonal basis. Each year was divided into four principal seasons, viz. winter, pre-monsoon, monsoon and post-monsoon. The percentages of significant trends obtained for each parameter in the different seasons are presented. Temperature anomalies are plotted, and it is observed that annual mean temperature, mean maximum temperature and mean minimum temperature have increased at the rate of 0.42, 0.92 and 0.09°C (100 year)$^{-1}$, respectively. On a regional basis, stations of southern and western India show a rising trend of 1.06 and 0.36°C (100 year)$^{-1}$, respectively, while stations of the north Indian plains show a falling trend of –0.38°C (100 year)$^{-1}$. The seasonal mean temperature has increased by 0.94°C (100 year)$^{-1}$ for the post-monsoon season and by 1.1°C (100 year)$^{-1}$ for the winter season.

Key words annual trend; India; Mann-Kendall test; percentage of significant trend; seasonal trend; temperature anomalies

Evaluation de tendances de température en Inde

Résumé L'impact du changement climatique devrait avoir des effets variables dans et entre les pays. Une information au sujet de ce changement est nécessaire aux échelles globale, régionale et de bassin, par rapport à une multiplicité d'enjeux. Nous avons cherché à identifier les tendances dans les séries de température de 125 stations réparties en Inde, dans son ensemble. Le test non-paramétrique de Mann-Kendall a été appliqué pour détecter les tendances monotones dans les séries de températures moyennes annuelles et saisonnières. Trois variables associées à la température, c'est-à-dire la moyenne, le maximum moyen et le minimum moyen, ont été considérées et analysées en annuel et en saisonnier. Chaque année a été divisée en quatre saisons principales: l'hiver, la pré-mousson, la mousson et la post-mousson. Les pourcentages de significativité de tendance obtenus pour chaque grandeur et chaque saison sont présentés. Les anomalies sont identifiées, et il apparaît que la température moyenne annuelle, la température maximale moyenne et la température minimale moyenne ont augmenté respectivement de 0.42, 0.92 et 0.09°C (100 ans)$^{-1}$. Du point de vue régional, les stations du sud et de l'ouest de l'Inde montrent des tendances croissantes à hauteur de 1.06 et 0.36°C (100 ans)$^{-1}$, respectivement, tandis que les stations des plaines du nord de l'Inde présentent une tendance décroissante de –0.38°C (100 ans)$^{-1}$. La température moyenne saisonnière a augmenté de 0.94°C (100 ans)$^{-1}$ pour la saison de post-mousson et de 1.1°C (100 ans)$^{-1}$ pour l'hiver.

Mots clefs tendance annuelle; Inde; test de Mann-Kendall; pourcentage de significativité de tendance; tendance saisonnière; anomalies de température

INTRODUCTION

Human activities have increased the atmospheric concentration of greenhouse gases changing the Earth's climate on both global and regional scales. There is evidence that the recent climate is the result of both natural and anthropogenic forcing. In recent years the potential impacts of climatic change and variability have received a lot of attention

from researchers. A comprehensive review of the potential impacts of climatic change is provided in IPCC (1998, 2001). According to IPCC (2001), increases in greenhouse gas concentrations increased the annual mean global temperature by $0.6 \pm 0.2°C$ since the late 19th century. Available records show that the 1990s have been the warmest decade of the millennium in the Northern Hemisphere and 1998 was the warmest year. Some of the largest changes have occurred in the high-latitude Northern Hemisphere land areas, where winter temperatures increased at rates greater than $0.8°C$ decade^{-1} across large parts of high-latitude North America, Europe and Asia since 1976 (IPCC, 2001). It is also reported that the concentration of greenhouse gases was the maximum in the history of the 19th century (Nakicenovic *et al.*, 2000). Estimates based on global circulation models, following increase in greenhouse gases at the current rate, suggest that the global mean surface temperature is expected to increase between 1.4 and 5.8°C by 2100 with respect to 1990 (IPCC, 2001). However, while globally averaged precipitation is projected to increase, both increases and decreases are expected at the regional scale. Other indications of the changing climate include retreating glaciers, rising sea level, reduction in sea-ice thickness and in snow cover. Studies related to snow and glaciers indicate that, under the warmer climate, glaciers are projected to continue their widespread retreat during the 21st century. The global mean sea level is likely to increase by 0.09–0.88 m between 1990 and 2100.

Temperature drives the hydrological cycle, influencing hydrological processes in a direct or indirect way. A warmer climate leads to intensification of the hydrological cycle, resulting in higher rates of evaporation and increase of liquid precipitation. These processes, in association with a shifting pattern of precipitation, will affect the spatial and temporal distribution of runoff, soil moisture, groundwater reserves and increase the frequency of droughts and floods. The future climatic change, though, will have its impact globally and will be felt severely in developing countries with agrarian economies, such as India. Surging population and associated demands for freshwater, food and energy would be areas of concern in the changing climate. Changes in extreme climatic events are of great consequence owing to the high vulnerability of the region to these changes. Parry *et al.* (2001) have shown that there is a steep rise in the water shortage curve when plotted against rise in temperature. They reported that this is due to large urban populations in China and India being newly exposed to risk.

REVIEW OF THE LITERATURE IN AN INDIAN CONTEXT

The surface temperatures over the region show a variety of trends in seasonal and annual patterns, and are greatly modified by altitude, location in relation to the sea coast and other such geographical features. In India some studies have been carried out to determine the changes in temperature and their association with climate change. Secular trends in the annual mean maximum and minimum temperatures over India were studied by Pramanik & Jagannathan (1954). They concluded that there is no general tendency for an increase or decrease in these temperatures. Jagannathan & Parathasarathy (1973) analysed the time series of mean annual temperatures over a set of eight Indian stations. They reported an increasing trend in the mean annual temperatures of Kolkata, Mumbai, Bangalore and Allahabad, and a decreasing trend at Cochin. Sarker & Thapliyal (1988) reviewed climate change over the previous 80 years and indicated a slight warming trend

in dry-bulb temperature; while rainfall showed no trend. The study by Srivastava *et al.* (1992) on decadal trends in climate over India gave the first indications that the diurnal asymmetry of temperature trends over India is quite different from that observed over many other parts of the globe. They found that maximum temperatures show much larger increasing trends than the minimum temperatures, over a major part of the country. A decreasing trend in temperature over most of the northern parts of the country (north of 23°N), coupled with an increasing trend over southern parts (south of 23°N), and an overall slightly increasing trend of the order of 0.35°C was observed during the last 100 years. Rupa Kumar *et al.* (1994) have shown that the countrywide mean maximum temperature has risen by 0.6°C, and the mean minimum temperature has decreased by 0.1°C. However, as the result from mean minimum temperatures is not statistically significant, they concluded that most of the increases in mean surface air temperature over India are due to the increase in daytime temperature. Pant & Kumar (1997) analysed the data for 1881–1997 and showed that there is a significant warming trend of 0.57°C per hundred years. The magnitude of warming is higher in the post-monsoon and winter seasons. The monsoon temperature does not show a significant trend in any major part of the country except for a significant negative trend over northwest India. No significant trends were obtained in the rainfall on either an annual or a seasonal basis. Sinha Ray & De (2003) have summarized existing information on climate change and on trends in the occurrence of extreme events over India. It is reported that rainfall and surface pressure averaged over the country as a whole show no significant trend. An increasing trend of the order of 0.35°C over the last 100 years has been observed in temperature records. Extreme maximum and minimum temperatures show an increasing trend in the south and a decreasing trend in the north.

Future warming scenarios have been generated for the Indian sub-continent using general circulation models (GCMs). The output from equilibrium GCM experiments shows that the temperature rise in northern India would be higher than that in southern India. The output from different GCM scenarios varies substantially, and the average change across India is predicted to be in the range of 2.3–4.8°C. On the other hand, taking the possible cooling effect of sulphate aerosols into account, Lal *et al.* (1995) suggested that the increase in the annual mean maximum and minimum surface air temperatures would be of the order of 0.7–1.0°C in the 2040s, in comparison to the 1980s.

Water resources play a vital role in the Indian economy. The water and agricultural sectors are likely to be worst affected by warmer climate. The major rivers of India, namely, the Indus, the Ganga and the Brahmaputra, originate from the Himalayas and receive a substantial amount of meltwater from snow and glaciers. Water yield for the Himalayan snow-fed rivers is roughly twice that of the peninsular rivers of south India. Singh *et al.* (1994, 1997) and Singh & Jain (2002) carried out some studies to estimate the contribution of snow and glaciers in the annual flows of a few Himalayan rivers. The results of these studies show that, on average, the Ganga at Deoprayag receives about 30% of its annual discharge from snow and glacier melt, the Chenab receives 49% and the Satluj receives 60%. Many studies have reported the recession of Himalayan glaciers (e.g. Gergan, 2002; Dobhal *et al.*, 2004). Increased temperatures are expected to reduce average flow of snow-fed rivers, coupled with an increase in peak flows and sediment yield. This would have major impacts on hydropower generation and urban water supply. Agricultural productivity is likely to suffer severely due to higher temperatures. Under warmer climate, the arid and semiarid regions could experience severe water

stress due to the decline in soil moisture. The amount of water evaporated from the land surface is an important criterion for the sustenance and development of vegetative life. The peninsular region of India includes large coastal areas. Under a warmer climate, the rise in sea level would cause submergence of vast areas of coastline. Aquaculture productivity is also likely to undergo changes as a result of temperature rise. The spatial distribution and magnitude of temperature trends in the region would help in obtaining climate change scenarios for such studies.

With the growing concern about climate change impacts, researchers have employed the nonparametric Mann-Kendall test (Mann, 1945; Kendall, 1975) to identify whether monotonic trends exist in hydrometeorological data such as temperature, precipitation and streamflow (Taylor & Loftis, 1989; McLeod *et al*., 1991; Yu *et al*., 1993; Burn, 1994; Douglas *et al*., 2000; Yue *et al*., 2003; Burn *et al*., 2004 and others). Kundzewicz & Robson (2004) have outlined and presented a brief overview of some of the tests. Application of trend tests may sometimes produce misleading results in the presence of serial correlation in the series. Burn *et al*. (2004) investigated trends in the streamflow series of the Liard River in northern Canada. Trends were investigated using the Mann-Kendall test, with a serial correlation approach. Kothyari & Singh (1996) carried out an investigation to identify rainfall and temperature trends in the Ganga basin in India and also in India as a whole. Their results showed that rainfall has a decreasing trend and temperature has an increasing trend. Mirza *et al*. (1998) analysed trends and persistence in precipitation in Ganga, Brahmaputra and Meghna river basins. Sharma *et al*. (2000) studied land-use, climatic and hydrological trends over the Kosi basin (54 000 km^2) in the central Himalayan region. The analysis of meteorological and hydrological time series from 1947 to 1993 showed some increasing tendency of temperature and precipitation.

The significant increase in the mean annual global surface air temperature during the past century is probably the most widely quoted aspect of climatic change. Identification of this warming and its comparison with that projected by the various GCMs, has prompted a large number of studies of temperature trends. Most of the temperature studies on India are confined to the analysis of annual and seasonal series of temperature for some individual stations or groups of stations. In such studies on the identification of trends over a region, the monthly mean temperature series of each station are usually converted into temperature anomaly series (i.e. deviations from the mean). These anomalies are then used to obtain the seasonal and spatial averages for long-term temperature change. In the present study, a nonparametric Mann-Kendall (MK) statistical test was applied to annual average temperature, annual average maximum temperature, annual average minimum temperature and average seasonal temperatures of 125 stations distributed throughout India. Annual and seasonal temperature anomalies were analysed on a country scale as well as a regional scale.

STUDY AREA AND DATA USED

Covering an area of 3.29×10^6 km^2, India is the world's largest peninsula, situated in south Asia. The Indian subcontinent is an excellent example of a monsoon-type climatic region. In a year, there are two types of monsoon current. and four principal seasons: winter (December–February); pre-monsoon (March–May); monsoon (June–August); and post-monsoon (September–November).

The temperature data of 125 stations distributed throughout India were collected from the India Meteorological Department and annual mean temperature, annual mean maximum temperature and annual mean minimum temperature series were prepared. Seasonal average temperature series, seasonal maximum temperature series and seasonal minimum temperature series were prepared for each principal season.

In regional analysis, problems occur in selecting stations with the same time frame. Comparison of results for the different time period leads to several observations (Burn *et al.*, 2004). It was found that 54 stations had a common data period of 1941–1999. In many other cases the starting year was the same but the ending year was earlier by a few years. While applying the test, varying lengths of data for different stations were considered, as bringing the data to a common period could have substantially reduced the length of a data set. An autocorrelation test (Yevjevich, 1971) was applied to test the randomness of the data sets and they were found to be random.

METHODOLOGY

Trends in data can be identified by using either parametric or non-parametric methods. In the recent past, both methods have been widely used for the detection of trends (e.g. WMO, 1988; Mitosek, 1992; Chiew & McMahon, 1993; Burn & Elnur 2002). The nonparametric tests are more suitable for non-normally distributed, censored data, including missing values, which are frequently encountered in hydrological time series (Hirsch & Slack, 1984).

Mann-Kendall (MK) test

The MK test used in the present study is based on the test statistic, *S*, defined as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}(x_j - x_k) \tag{1}$$

where $\mathrm{sgn}(\theta) = 1$ if $\theta > 0$; $\mathrm{sgn}(\theta) = 0$ if $\theta = 0$; and $\mathrm{sgn}(\theta) = -1$ if $\theta < 0$. Mann and Kendall have documented that when $n \geq 10$, the statistic S is approximately normally distributed with the mean and the variance as follows:

$$E[S] = 0 \tag{2}$$

$$\mathrm{var}[S] = (n(n-1)(2n+5) - \sum_t t(t-1)(2t+5))/18 \tag{3}$$

where *t* is the extent of any given tie (number of *x*s involved in a given tie), and $\sum t$ denotes the sum of the terms $t(t-1)(2t+5)$, which are evaluated and summed for each tie of the *t* number in the data. The standard normal variable *Z* is computed by:

$$Z = \left\{ \frac{S-1}{[\mathrm{var}(S)]^{1/2}} \right\} \qquad \text{if } S > 0$$

$$Z = 0 \qquad \text{if } S = 0 \tag{4}$$

$$Z = \left\{ \frac{S+1}{[\mathrm{var}(S)]^{1/2}} \right\} \qquad \text{if } S < 0$$

The values of test statistics are computed and it may be seen that, if the value lies within the limits –1.96 and 1.96, the null hypothesis of having no trend in the series cannot be rejected at the 5% level of significance using a two-tailed test.

Determination of anomalies

For better understanding of the observed trends, the temperature anomalies were computed. These temperature anomalies were plotted against time and the linear trends observed were represented graphically. The anomalies for maximum, minimum and mean temperatures for different regions and seasons with respect to their mean of 59 years (1941–1999) are shown in Figs 1–3. The linear trend value, represented by the slope of a simple least-square regression line with time as the independent variable gives the magnitude of rise or fall in temperature. Although a maximum possible number of stations was used, it is necessary to confirm the results with a more homogeneous and updated data set.
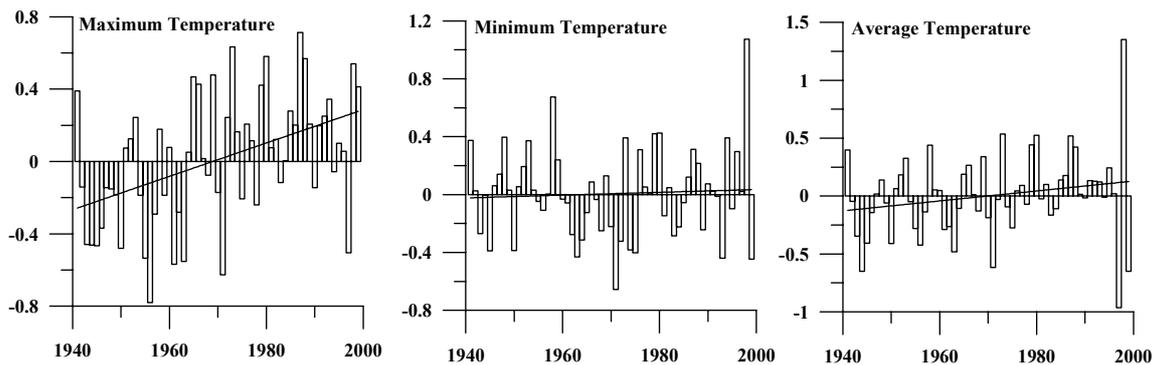

Fig. 1 Anomalies in annual temperature.

Table 1 Summary of results (number of stations = 125).

| Variable related to temperature	Number of stations with falling trends	Number of stations with rising trends	Significant trends (%)
Annual average	17	53	56
Annual average maximum	8	63	56
Annual average minimum	31	33	51
Winter average	19	39	46
Winter average maximum	17	48	52
Winter average minimum	15	32	37
Pre-monsoon average	35	23	46
Pre-monsoon average maximum	18	42	48
Pre-monsoon average minimum	42	15	45
Monsoon average	18	27	36
Monsoon average maximum	3	47	40
Monsoon average minimum	41	22	50
Post-monsoon average	6	59	52
Post-monsoon average maximum	4	73	61
Post-monsoon average minimum	10	38	38
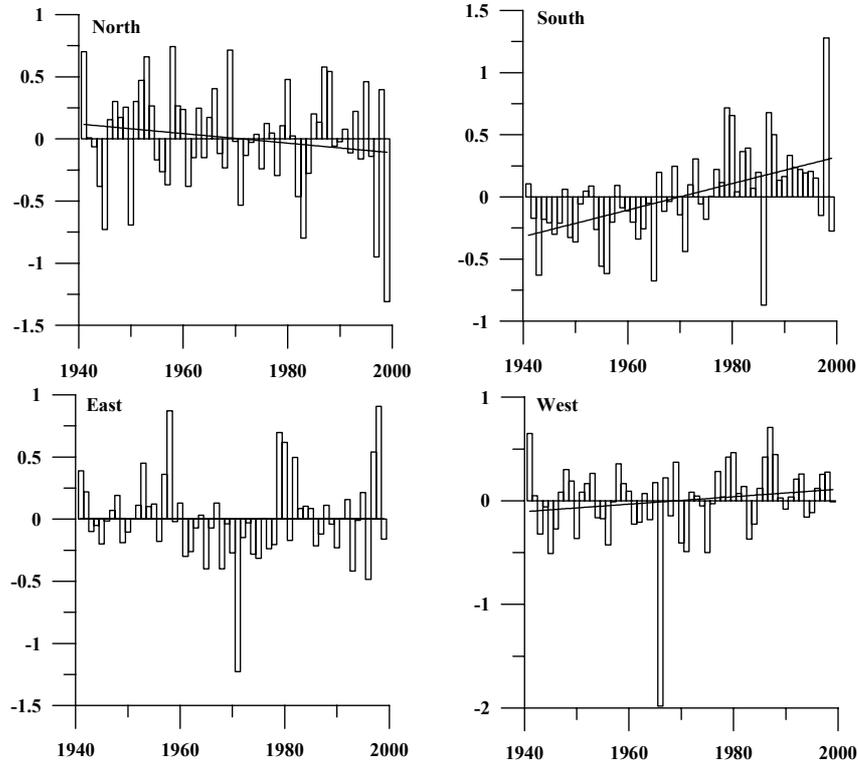
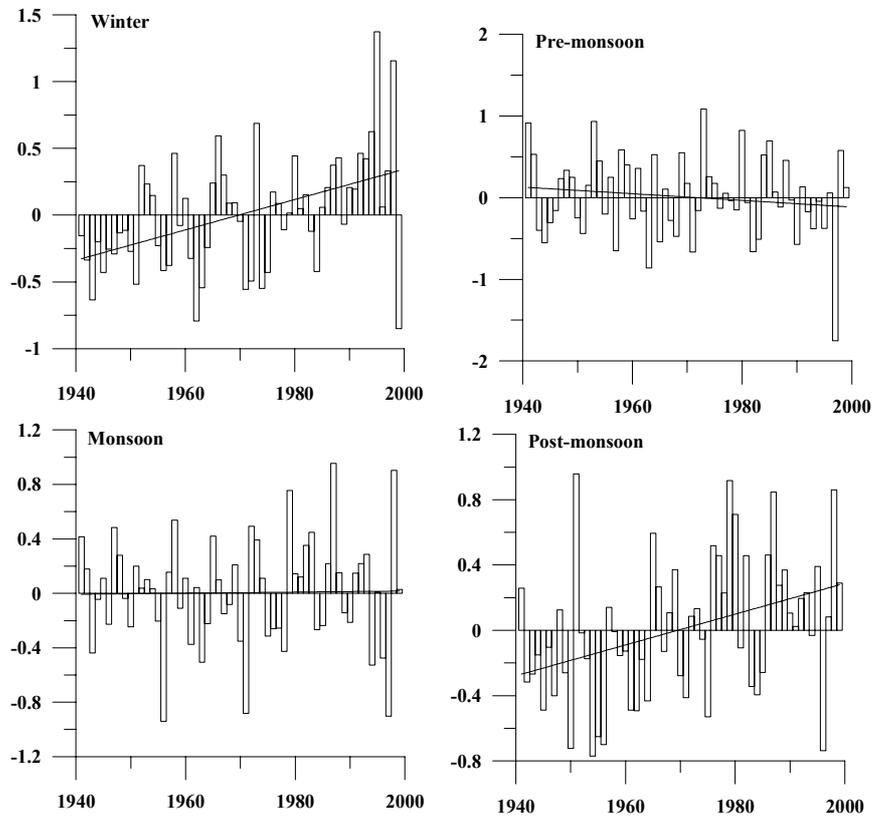**Fig. 2** Anomalies in annual mean temperature of different regions.

Fig. 3 Anomalies in seasonal mean temperature.

RESULTS AND DISCUSSION

The Mann-Kendall test was applied on three different parameters of annual and seasonal temperatures. A brief summary of results obtained is given in Table 1.

Annual trends

It is observed that the percentage of significant trends obtained for the three annual temperature parameters, viz. annual mean, annual mean maximum and annual mean minimum, are 56, 56 and 51, respectively. The mean maximum temperature series shows a rising trend at 63 stations and a falling trend at eight stations. The mean minimum temperature shows a rising trend at 33 stations and a falling trend at 31 stations. In the annual mean temperature series, a rising trend is observed at 53 stations and a falling trend at 17 stations. The distribution of observed trend is shown in Fig. 4. From Fig. 4, it may be seen that most of the stations located in the south, central and western parts of India show a rising trend and some stations located in the north and northeastern India show a falling trend in annual mean temperature. This falling trend in annual mean temperature may be due to the falling trend in the annual mean minimum temperatures of these stations—most of which are located in the foothills of the Himalayas. The temperature anomalies for the three variables are shown in Fig. 1. The annual mean temperature has increased by 0.42°C during the last 100 years. A rise of 0.92°C (100 year)$^{-1}$ in the annual mean maximum temperature and a rise of 0.09°C (100 year)$^{-1}$ in mean minimum temperature are observed. The temperature anomalies for annual mean temperatures of different regions of India are presented in Fig. 2; Fig. 3 depicts the anomalies in seasonal mean temperatures; and the trends in annual mean temperatures in different regions are shown in Fig. 4. The stations located in southern and western regions show a rising trend of 1.06 and 0.36°C (100 year)$^{-1}$, respectively, while the stations of the northern plains show a falling trend of –0.38°C (100 year)$^{-1}$.
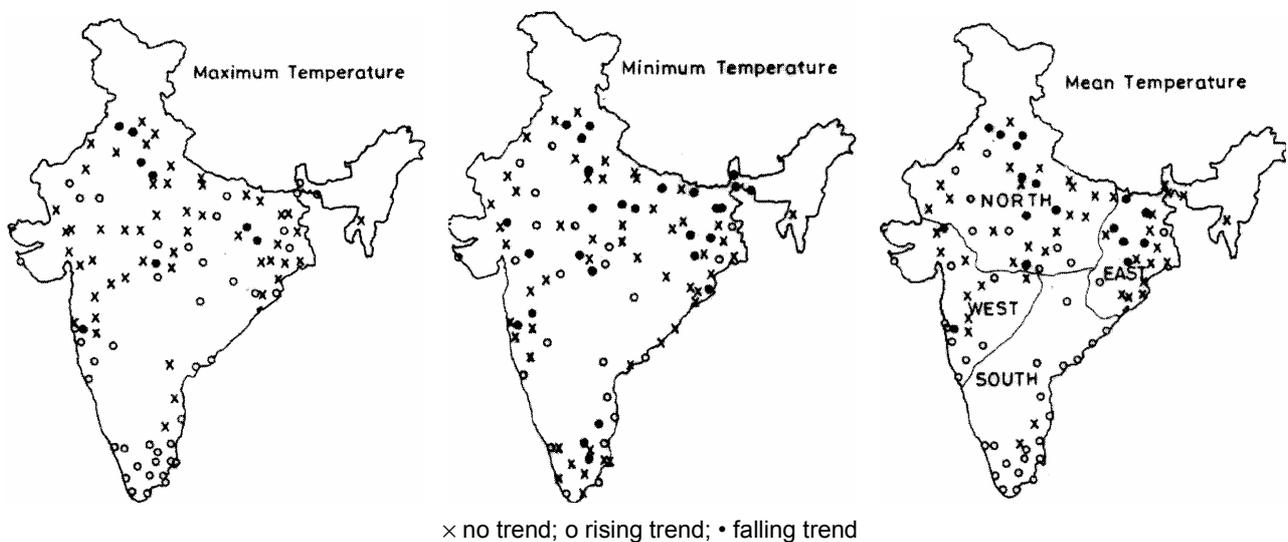

× no trend; o rising trend; • falling trend

Fig. 4 Observed trends in annual mean temperatures.

Seasonal trends

The percentage of significant trends for the three variables in the winter season was found to be 46, 52 and 37, respectively. The number of stations showing a rising trend in the mean maximum winter temperature is 48 and that with falling trend is 17. The mean minimum winter temperature series shows 32 stations with a rising trend and 15 stations with a falling trend. In the mean winter temperature series, a rising trend is observed at 39 stations and a falling trend at 19 stations. The distribution of stations having winter temperature trends is shown in Fig. 5. From this figure, it may be observed that most of the stations in the coastal and southern areas show an increasing trend, while a falling trend is exhibited by some stations in north, central and eastern India. There is a rise in temperature of 1.1°C (100 year)$^{-1}$ during the winter and 0.94°C (100 year)$^{-1}$ during the post-monsoon season.

For the pre-monsoon season, the percentage of significant trends observed is approximately in the same range for all the three variables: viz. 46, 48 and 45 respectively. But for the mean maximum temperature series, 42 stations show a rising trend and 18 stations a falling trend, whereas for mean minimum temperature, 15 stations show a rising trend and 42 stations a falling trend. The combined effect of both of these variables is observed in mean pre-monsoon temperature trends, with a rising trend at 35 stations and a falling trend at 23 stations. The distribution of these stations and observed trends are shown in Fig. 6. It is apparent that most of the stations in the eastern region and in the foothills of the Himalayas show a falling trend. Some stations in western and southern regions also show a falling trend.

The percentage of significant trends observed for three variables in the monsoon season is 36, 40 and 50, respectively, which is lower as compared to other seasons. In a similar pattern to that observed for the pre-monsoon season, 47 stations show a rising trend and three a falling trend in the monsoon season mean maximum temperature series. In the mean minimum temperature series, a rising trend exists for 22 stations and a falling trend for 41 stations. For the mean monsoon temperature series, 27
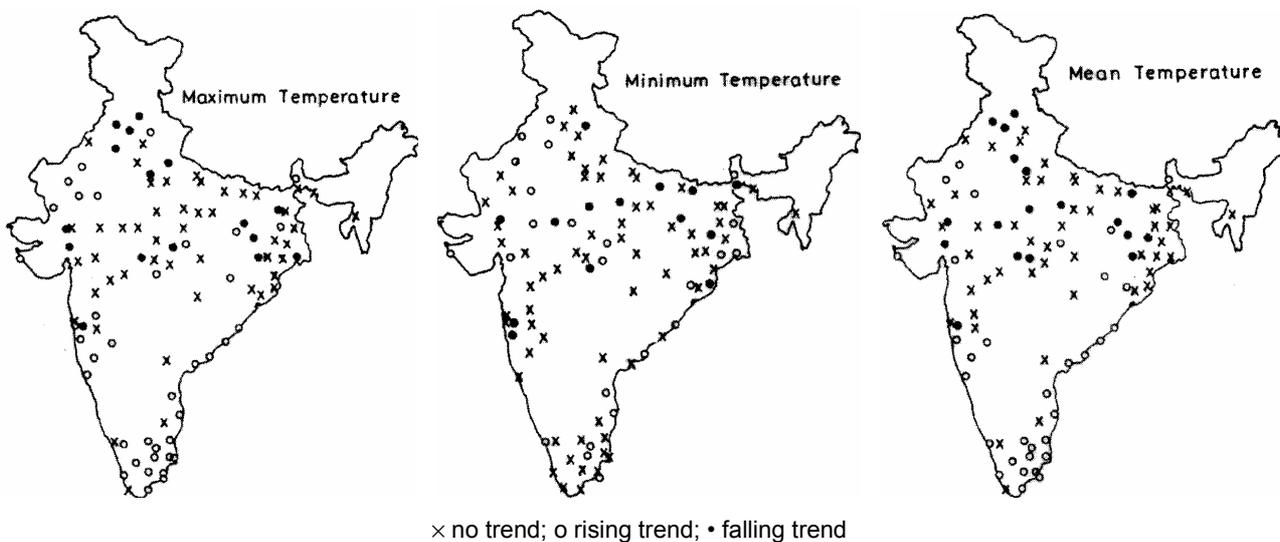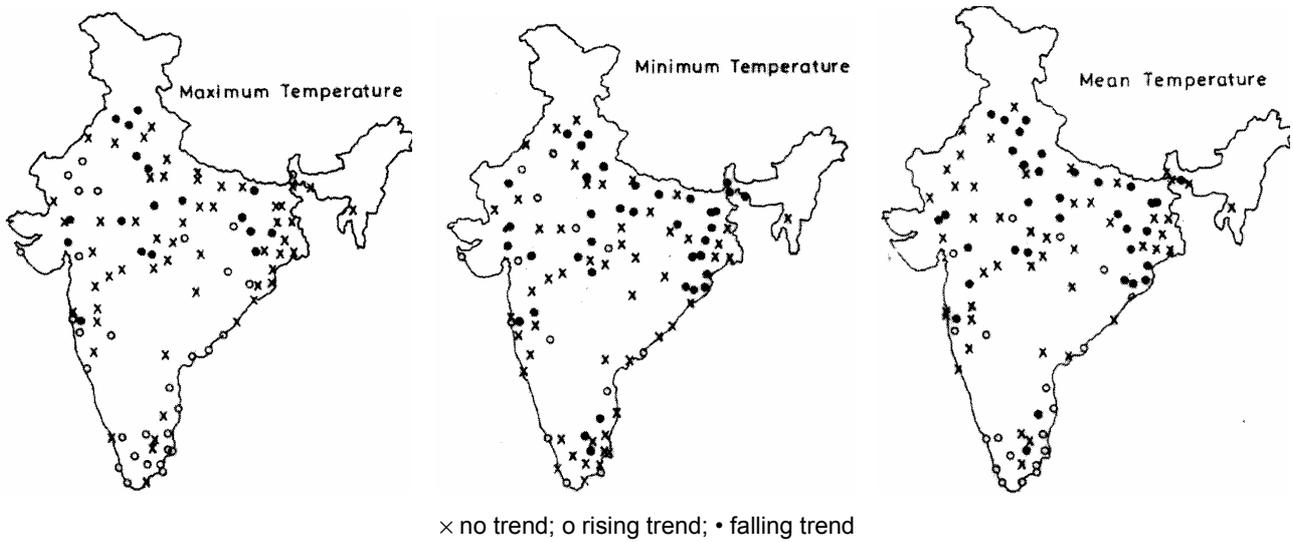

× no trend; o rising trend; • falling trend

Fig. 5 Observed trends during the winter season.

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× no trend; o rising trend; • falling trend

Fig. 6 Observed trends during the pre-monsoon season.

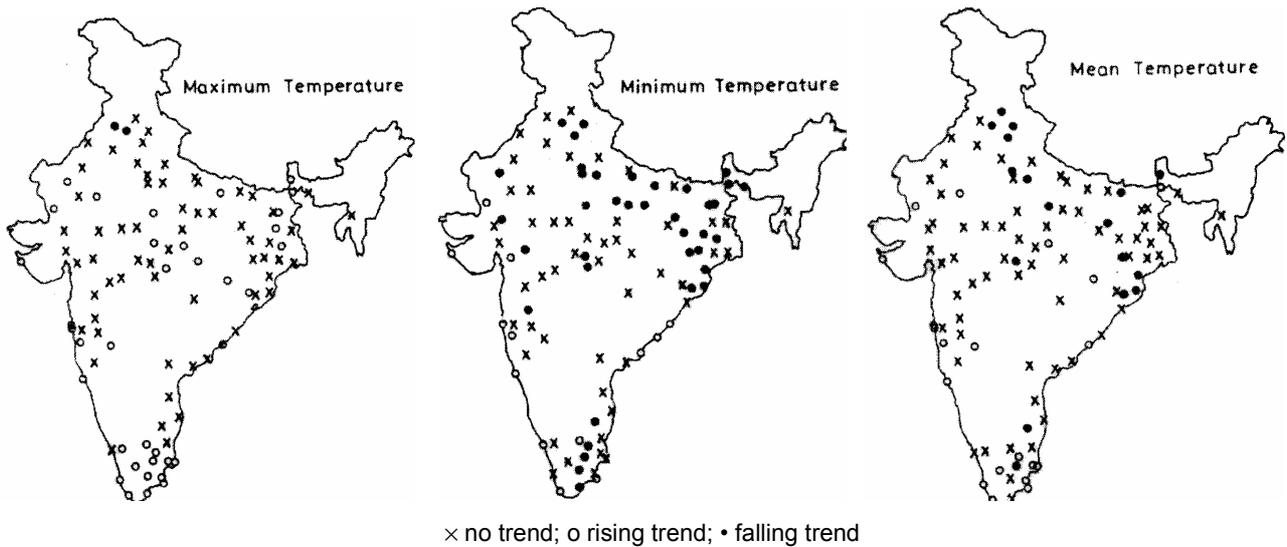× no trend; o rising trend; • falling trend

Fig. 7 Observed trends during the monsoon season.

stations show a rising trend and 18 stations a falling trend. The observed trends at different stations during the monsoon season are shown in Fig. 7.

The percentage of significant trends for the three variables in the post-monsoon season is 51, 61 and 38, respectively. In the mean maximum temperature series, 73 stations show a rising trend and four a falling trend, while in the mean minimum temperature series, 38 stations have a rising trend and 10 a falling trend. In the mean post-monsoon temperature series, 59 stations show a rising trend and six a falling trend. The distribution of observed trends during the post-monsoon season is shown in Fig. 8. It may be seen that a rising temperature trend dominates all over India during this season.
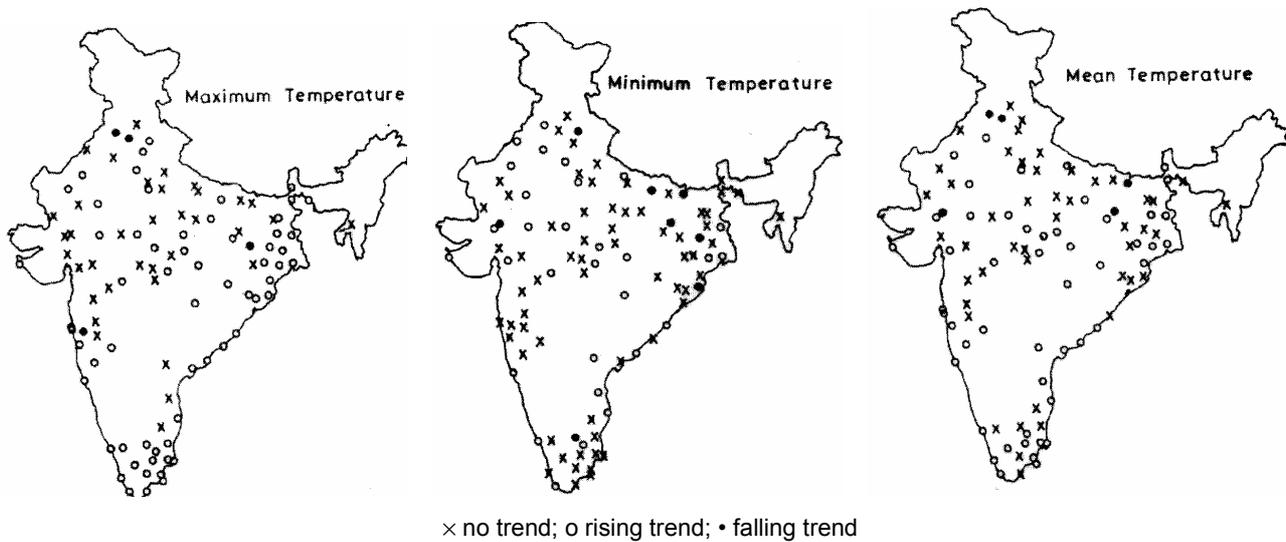
× no trend; o rising trend; • falling trend

Fig. 8 Observed trends during the post-monsoon season.

CONCLUSION

The global average surface temperature has increased by 0.6 ± 0.2°C over the last century (IPCC, 2001) and it is expected that, by 2100, the increase in temperature could be 1.4–5.8°C. Temperature changes have not been uniform globally, but have varied over regions and different parts of the lower atmosphere. In the Indian context, a number of researchers have reported a rise in temperature. However, these studies are based on individual sites or on a small number of sites. In the present study, an analysis was carried out to identify the trends in average, maximum and minimum temperatures on annual and seasonal data of 125 stations distributed over the whole of India.

For the identification of trend, the non-parametric Mann Kendall test was applied. The trend patterns were identified for every individual station. Three variables of temperature i.e. mean, mean maximum and mean minimum were considered in the analysis for different seasons as well as for the year as a whole. It was found that the percentage of significant trends obtained is high enough. The trends observed for the three variables on both an annual and a seasonal basis has been shown. It was found that there is a rising trend in most cases, except for mean pre-monsoon temperature, mean monsoon temperature, pre-monsoon mean minimum temperature and monsoon mean minimum temperature. From the anomalies plotted, it may be seen that there is an increase of 0.42°C (100 year)$^{-1}$ in the annual mean temperature, 0.92°C (100 year)$^{-1}$ in the mean maximum temperature and 0.09°C (100 year)$^{-1}$ in the mean minimum temperature. The south Indian stations show a rise of 1.06°C (100 year)$^{-1}$ in mean regional temperature; west Indian stations show a rise in temperature of the order of 0.36°C (100 year)$^{-1}$; north Indian stations show a fall in temperature of the order of –0.38°C (100 year)$^{-1}$. Averaged for all seasons, there is a rise of 1.1°C (100 year)$^{-1}$ in the mean winter temperature, 0.94°C (100 year)$^{-1}$ in mean post-monsoon temperature, and a fall of –0.40°C (100 year)$^{-1}$ in mean pre-monsoon temperature.

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