Variations in diurnal temperature range over India: Under global warming scenario

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[1] Annual, seasonal, and monthly trends in surface air temperature were examined over India during the period 1901–2003. Besides this, annual and seasonal trends were also scrutinized in view of global warming concerns during the 2 non-global (1901–1909 and 1946–1975) and global (1910–1945 and 1976–2003) warming periods as defined by Intergovernmental Panel on Climate Change. A significant increasing trend of 0.743, 0.224, 0.484, and 0.52°C (100 yr)$^{-1}$ has been observed in maximum ($T_{\max}$), minimum ($T_{\min}$), mean (T_{mean}) temperatures, and diurnal temperature range (*DTR*; $T_{\max} - T_{\min}$), respectively during the period 1901–2003. The annual temperatures (T_{mean}, $T_{\min}$, and $T_{\max}$) show a cooling (warming) tendency during the non-global (global) warming periods, apart from the second non-global warming period of $T_{\max}$. The seasonal trends in $T_{\min}$ and T_{mean} also show similar behavior; whereas, $T_{\max}$ shows warming in all sub-periods, excluding the first non-global warming period of the pre-monsoon and monsoon. Seasonal analysis depicts that, both post-monsoon and winter seasons are getting warmer with regard to $T_{\max}$ and $T_{\min}$. During the analysis as well as in non-global and global warming periods, annual *DTR* has increased. *DTR* increases in all seasons, with the largest increase in winter and the smallest in post-monsoon; whereas monthly analysis reveals that all the months, except March, October, and November are contributing significantly to the annual increase of *DTR*. The partial correlation analysis reveals that the total cloud cover along with the secondary factors like precipitation and soil-moisture are responsible for increase in *DTR* over India during the period 1948–2003.

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1. Introduction

[2] Global warming refers to the increase in the average temperature of the Earth's near surface air and oceans. According to the Fourth Assessment Report by the *Intergovernmental Panel on Climate Change* (*IPCC*) [2007], the global mean temperature (T_{mean}), averaged over land and ocean surfaces, increased by 0.76°C ± 0.19°C between the first 50 years of the instrumental record (1850–1899) and the last 5 years (2001–2005) with a linear warming trend of 0.74°C ± 0.18°C over the last 100 years (1906–2005).

[3] In recent decades, the rising of global atmospheric temperature is one of the major concerns because main manifestation of global warming is attributed to the maximum ($T_{\max}$) and minimum ($T_{\min}$) temperatures, due to their association with cloudiness, winds, soil moisture, precipitation, and humidity over land areas [*IPCC*, 1990]. The rise in $T_{\max}$ and $T_{\min}$ is not uniform across the world. Such an asymmetry between $T_{\max}$ and $T_{\min}$ over the world, causes increase/decrease in diurnal temperature range (*DTR*; difference of $T_{\max}$ and $T_{\min}$).

[4] In many parts of the world, $T_{\min}$ is increasing at a much faster rate than $T_{\max}$ and hence causing *DTR* to decrease [*Karl et al.*, 1991, 1993; *Kukla and Karl*, 1993; *Easterling et al.*, 1997]; whereas in some parts of New Zealand [*Salinger*, 1995] and mountain top stations of central Europe [*Weber et al.*, 1994] the rate of increase of $T_{\max}$ and $T_{\min}$ is similar and hence not much change in *DTR* is observed.

[5] *Vose et al.* [2005] analyzed global temperature data for the period 1950–2004 and reported that during the analysis period, $T_{\min}$ has increased (0.204°C dec^{-1}) more rapidly than $T_{\max}$ (0.141°C dec^{-1}), resulting a significant decrease in *DTR*; whereas, during recent decades (1979–2004), the increase in $T_{\max}$ is comparable to $T_{\min}$ which weakens the negative trend in *DTR*. Further, it was also stated that the pattern of *DTR* is less consistent and for some regions like northern Eurasia, western North America, Australia, and the Indian subcontinent an increase has been observed.

[6] In many previous studies it was proposed that the increase in cloud cover, precipitation, and soil moisture [*Karl et al.*, 1993; *Dai et al.*, 1997, 1999] are mainly responsible for the reduction in *DTR*; whereas for China [*Liu et al.*, 2004], the decrease in solar irradiance (unbalanced

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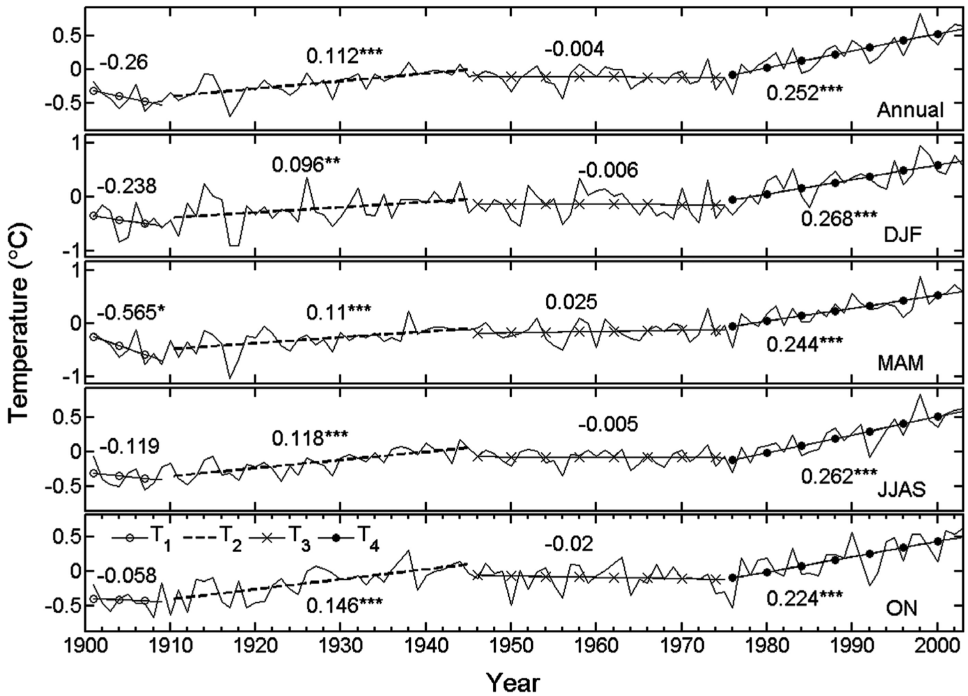

Figure 1. Variation and linear trends in annual and seasonal global T_{mean} (http://www.cru.uea.ac.uk/cru/data/temperature) during T_1 (first non-global warming period; 1901–1909), T_2 (first global warming period; 1910–1945), T_3 (second non-global warming period; 1946–1975), and T_4 (second global warming period; 1976–2003). Values along the trend lines are the rate of change [°C (10 yr)$^{-1}$]. * 90% CL; ** 95% CL; and *** 99% CL. CL, confidence level.

between day and night having its greatest effect on $T_{\max}$ rather than $T_{\min}$) plays a key role in its reduction. The increase in other factors, such as atmospheric aerosols (cooling effect on $T_{\max}$ and also responsible for increase in cloudiness [*Hansen et al.*, 1995; *Dai et al.*, 1997]) and greenhouse gases also causes decrease in *DTR*. Furthermore, the influence of the local effects, such as urban growth, irrigation, desertification, and variations in local land use, on *DTR* were also reported [*Karl et al.*, 1993].

[7] The increase in clouds will tend to decrease $T_{\max}$, whereas its net effect on $T_{\min}$ is relatively small due to the fact that clouds reflect sunlight which reduces afternoon temperatures and thus $T_{\min}$, but on the other hand it also enhances downward longwave radiation which increases $T_{\min}$ and hence causes *DTR* to decrease. An increase in precipitation also contributes to decrease in *DTR* through the surface evaporative cooling [*Dai et al.*, 1997]. Evapotranspiration, associated with soil moisture and precipitation, balances solar heating, which in turn causes decrease in $T_{\max}$ [*Dai et al.*, 1999]. In addition to this, it was also reported that the influence of atmospheric water vapor on *DTR* is very small because its effect on $T_{\max}$ and $T_{\min}$ are comparable.

[8] Several studies were also performed over the Indian region to observe the temperature changes in the changing climate. *Kumar et al.* [1994] analyzed temperature data for the period 1901–1987 and reported that $T_{\max}$ has significantly increased during the analysis period, while $T_{\min}$ is almost stable, resulting to an increase in *DTR*. Further, it was also stated that during winter and post-monsoon seasons the increase in $T_{\max}$ is prevalent over major parts of India. Thus the diurnal asymmetry of temperature over India is quite different from the other parts of the world.

[9] *Kothawale and Rupa Kumar* [2005] analyzed Indian temperature data (1901–2003) and reported that the annual T_{mean} has increased at rate of 0.05°C (10 yr)$^{-1}$, while $T_{\min}$ showed a weak, statistically insignificant increasing trend. Additionally, it was also stated that during recent decades (1971–2003) an accelerated warming in T_{mean} (0.22°C (10 yr)$^{-1}$) has been observed, which is evident from $T_{\max}$ and $T_{\min}$.

[10] *Kothawale et al.* [2010] analyzed seasonal and annual trends in surface air temperature over India and 7 homogeneous regions and reported a significant increasing trend in annual T_{mean} (0.51°C (100 yr)$^{-1}$), $T_{\max}$ (0.72°C (100 yr)$^{-1}$), and $T_{\min}$ (0.27°C (100 yr)$^{-1}$). Further, the significant influence of El Niño Southern Oscillation events on temperature anomalies over India was also scrutinized during certain seasons.

[11] In the present study, the annual and seasonal trends in surface air temperature ($T_{\max}$, $T_{\min}$, and T_{mean}) are examined over India during the analysis period (1901–2003) as well as in the 2 non-global and global warming periods as shown in Figure 1, defined by IPCC, to see how it corresponds to global change. Besides this, monthly long-term trends are also scrutinized to find its contribution in annual and seasonal temperature variations. *DTR* demonstration on regional basis assumes special importance in context of global warming because its pattern is not uniform across the globe. Thus, its variation and linear trends are analyzed on annual, seasonal, and monthly basis, in order to examine its behavior. Further, an attempt has been made to investigate

the plausible factor/factors responsible for the increase in *DTR* over India.

[12] The data used in the present study are described in section 2. Section 3 provides the method of analysis. The results obtained from trend analysis on annual, seasonal, and monthly basis are given in 4.1–4.3, whereas section 4.4 discusses the possible factors responsible for changes in *DTR*. Section 5 provides the summary and conclusion.

2. Data

[13] Monthly temperature ($T_{\max}$ and $T_{\min}$) data used in the present study, over the network of 121 stations [see *Kothawale and Rupa Kumar,* 2005, Figure 1], are identical to those used by *Pant and Rupa Kumar* [1997] over Indian region for the period 1901–1990, which were initially sourced from the monthly weather records of the India Meteorological Department (IMD). From 1991 onwards, up to 2003 the data have been updated from the Indian Daily Weather Reports (IDWRs) published by the IMD. Possible inhomogeneities in the station data due to site, instrumentation, and exposure changes have been well examined by IMD. Around the year 1926, the exposure of the thermometers had been changed when IMD has decided to install the thermometers in the standard 'Stevenson Screen' instead of in the old type 'thatched sheds'. Relative observations of temperature readings in the 'shed' and 'screen' were made at least 2 years at all the stations to estimate the bias. Then accordingly the earlier records were adjusted. The detailed description is given by *Rupa Kumar and Hingane* [1988].

[14] *Kothawale and Rupa Kumar* [2005] converted the available station temperature data into monthly anomaly time series with reference to the respective station normal values for the period 1901–2003. The stationwise monthly temperature anomaly time series are then objectively interpolated onto 0.5° × 0.5° grid for the entire period of 1901–2003. Further, the climatological normals (1951–1980) of temperature at 388 stations have been interpolated onto the same grid, resulting in high-resolution grid point temperature climatology for India. The gridded monthly anomaly values are then added to the gridded climatology based on 388 stations there on producing a long-term gridded data set of actual temperatures over India for the period 1901–2003. The monthly temperature data used in present study for all India is the simple average of the constituent grid point data of the region, obtained from the Indian Institute of tropical Meteorology (IITM; http://www.tropmet.res.in).

[15] In order to investigate the possible factor (s) responsible for change in *DTR* over India during the period 1948–2003, through partial correlation analysis; precipitation, total cloud cover, surface wind speed, top 10-cm soil moisture content, and downward solar radiation flux (solar irradiance) have been used.

[16] The monthly precipitation data used in the present study is based on the network of 306 rain gauge stations that covers 30 meteorological subdivisions from all over India [*Parthasarathy et al.*, 1994].

[17] Since the long-term observational data for the variables like total cloud cover, surface wind speed, top 10-cm soil moisture content, and solar irradiance are not available for India therefore, they are from the NCEP/NCAR reanalysis project [*Kalnay et al.*, 1996] for the period 1948–2003. Among these the total cloud cover, top 10-cm soil moisture content, and solar irradiance are class 'C Variables' which are completely determined by the model, forced by the data assimilation to remain close to the atmosphere [*Kalnay et al.*, 1996], while surface wind speed (at lowest sigma level) belongs to class 'B Variables' influenced by the observations as well as by the model. In class 'C', there are no observations directly affecting the variable, so that it is derived solely from the model fields.

[18] The analysis system and the model remain unchanged throughout the analysis period. Therefore, the reanalyzed data is expected to be free from any artificial climate jumps. But the observing system has evolved. The evolution of the global observing system can be separated into three major phases: (1) the "early" period, 1940s to 1957 (International Geophysical Year), during which the first upper-air observations were established; (2) the "modern rawinsonde network" from 1958 to 1978; and (3) the "modern satellite era" from 1979 to present [*Kistler et al.*, 2001]. The detailed description about how, the observing system has evolved is discussed by *Kistler et al.* [1999].

[19] *Kistler et al.* [1999] describes the various sources of observations that are placed together for the reanalysis project and list each data source as a function of time. The Binary Universal Format Representation (BUFR) observational data archive includes "events" or metadata associated with the observation, such as information about quality control and the deviation of the observation from the background as well as from the analysis [*Woollen and Zhu*, 1997]. The records for the bulk of the source archive data received at NCEP for the reanalysis project are given by *Kistler et al.* [1999].

[20] The most important components of the reanalysis system are the 'quality control' and 'monitoring' of rawinsondes. This includes two quality control systems: optimal interpolation quality control [*Woollen*, 1991; *Woollen et al.*, 1994] for all observations and complex quality control for heights and temperature program [*Collins*, 1999]. The detailed description about the quality control of data is given by *Kalnay et al.* [1996] and *Kistler et al.* [1999].

[21] There is deficiency of observational data for studying such relations, therefore, it is imperative to use the reanalysis products that serve better approximates of real world yet, the model estimates are not perfect. Reanalysis data set is quite good as a first guess for studying the variability as well as its mechanisms, especially for the data-void regions or for the variables whose long-term observational data is not present.

[22] In order to see the effect of global warming on the global T_{mean} on annual and seasonal basis, and to examine whether the variation of surface air temperature trends over Indian region is in accordance with it or not, the global temperature anomalies from the Climate research Unit (CRU; http://www.cru.uea.ac.uk/cru/data/temperature) is used. The land air temperature anomalies are at 5° × 5° grid, computed with respect to the base period 1961–1990.

3. Method of Analysis

[23] According to *IPCC* [2001] report that most of the global surface temperature increase has occurred in two

Table 1. Annual and Seasonal Long-Term Temperature Trends (°C (100 yr)$^{-1}$) Over Indian Region During the Period 1901–2003[a]

Season	$T_{\max}$	$T_{\min}$	T_{mean}	DTR
Annual	0.743*** (99%)	0.224** (95%)	0.484*** (99%)	0.52*** (99%)
DJF	1.043*** (99%)	0.377** (95%)	0.71*** (99%)	0.666*** (99%)
MAM	0.629*** (95%)	0.174	0.402** (90%)	0.455*** (99%)
JJAS	0.464*** (95%)	−0.1	0.182*	0.564*** (99%)
ON	1.03*** (99%)	0.668*** (99%)	0.849*** (99%)	0.362

[a]From Student's t-test: * 90% CL; ** 95% CL; and *** 99% CL. CL, confidence level. Trend's significance from Mann-Kendall statistics are given in parentheses.

periods namely 1910–1945 and since 1976. Therefore, in the present study the analysis period has been divided into four sub-periods as follows: first non-global warming period (1901–1909; T_1), first global warming period (1910–1945; T_2), second non-global warming period (1946–1975; T_3), and second global warming period (1976–2003; T_4) as shown in Figure 1.

[24] In the present study, long-term trends in temperature ($T_{\max}$, $T_{\min}$, and T_{mean}) and *DTR* (difference between the mean monthly $T_{\max}$ and $T_{\min}$, [*Karl et al.*, 1993; *Kukla and Karl*, 1993]) are analyzed on annual, seasonal (pre-monsoon (March–May, MAM); monsoon (June–September, JJAS); post-monsoon (October–November, ON); and winter (December–February, DJF)), and monthly basis. Further, the annual and seasonal temperature trends in the non-global and global warming periods are also examined, to see the effect of global warming on it.

[25] For identifying the trend, the linear least squares fitting method has been used and its significance was examined by parametric two-tailed Student's t-test. The central limit theorem ensures that the parametric tests work well with large samples, even if the population data is non-Gaussian. Parametric tests are robust to deviations from Gaussian distribution, so long as the samples are large and the non-parametric tests work well with large samples coming from Gaussian distribution. In other words, for large data sets it does not really matter whether the data comes from Gaussian or non-Gaussian population, because the non-parametric tests are so powerful and the parametric tests are so robust. But for small data sets it presents a dilemma. The non-parametric (parametric) test is not powerful (robust), if the sample data comes from Gaussian (non-Gaussian) population. Since the temperature data used in this study is Gaussian (normally distributed) therefore, for examining the significance of long-term as well as sub-period's trend, parametric two-tailed Student's t-test has been applied. The significance of long-term trends is also further verified by using non-parametric Mann-Kendall statistics [*Joshi and Pandey*, 2011; *Khambhammettu*, 2005].

[26] In the present study, the long-term trends are expressed in the unit °C (100 yr)$^{-1}$, while the sub period's (T_1, T_2, T_3, and T_4) trends are shown in the unit °C (10 yr)$^{-1}$.

[27] Since the variables, for example, total cloud cover, surface wind speed, top 10-cm soil moisture content, and solar irradiance are from NCEP/NCAR reanalysis project, therefore, before doing any analysis the IMD grid has been used to mask out the oceanic regions from the reanalysis data and the reanalysis data is regridded onto the IMD grid. Bilinear interpolation technique has been used for regridding the reanalysis data onto the IMD grid.

4. Results

[28] Figure 1 shows the annual and seasonal global T_{mean}, averaged over the land surface. It has been observed that in the non-global warming periods the annual global T_{mean} shows decreasing tendency, while during global warming periods it increases significantly. More or less the similar behavior, i.e., the decreasing/increasing trends in the non-global/global warming periods has also been observed in the seasonal global T_{mean} as shown in Figure 1. Now, in order to see that whether the effect of global warming is limited up to the global basis or it also affects in a similar fashion the surface air temperature over Indian region, the long-term trend analysis along with the sub period's trend, i.e., the trends in non-global and global warming periods, are carried out in the following sub-sections.

4.1. Annual Trends

[29] The annual long-term temperature ($T_{\max}$, $T_{\min}$, T_{mean}, and *DTR*) trends during the analysis period (1901–2003) has been tabulated in annual entries in Table 1. The linear least squares fitting method shows (figure not shown) an increasing trend of 0.743, 0.224, 0.484, and 0.52°C (100 yr)$^{-1}$ in $T_{\max}$, $T_{\min}$, T_{mean}, and *DTR*, respectively. The trends observed in $T_{\max}$, $T_{\min}$, and T_{mean} are analogous to that obtained previously by *Kothawale et al.* [2010]. Now to quantify the significance of the trends, two-tailed Student's t-test has been applied and its results are further verified by using Mann-Kendall statistics.

[30] The results of two-tailed Student's t-test indicates that $T_{\max}$, T_{mean}, and *DTR* are significant at 99% confidence level (CL), whereas $T_{\min}$ is significant at 95% CL (which is in contradiction to *Kothawale and Rupa Kumar* [2005]). The accelerated and significant warming (0.186°C (10 yr)$^{-1}$; significant at 99%) observed in $T_{\min}$ (Figure 2) during the recent decades, i.e., second global warming period, might be the cause of long-term significant increase in annual $T_{\min}$; Mann-Kendall statistics also reveals the same, as tabulated in annual entry for $T_{\min}$ in Table 1.

[31] The annual $T_{\max}$, $T_{\min}$, T_{mean}, and *DTR* along with the trend lines for the periods 1901–1909, 1910–1945, 1946–1975, and 1976–2003 are presented in Figure 2. On close inspection, it has been observed that the annual temperatures (T_{mean}, $T_{\min}$, and $T_{\max}$; Figure 2) show a cooling/warming tendency during the non-global/global warming periods, except in the second non-global warming period of $T_{\max}$.

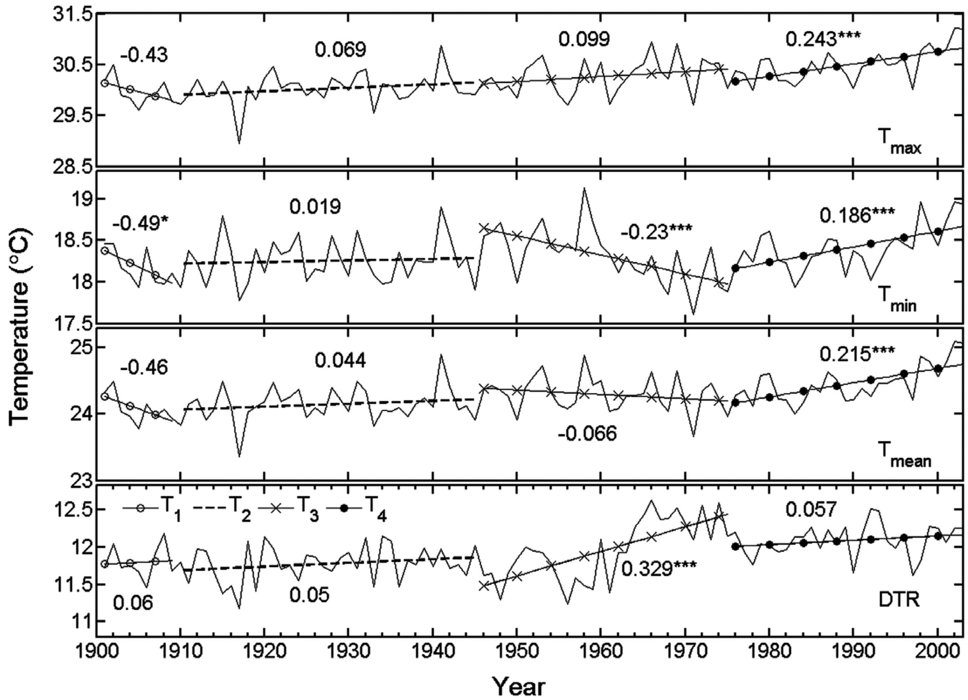

Figure 2. Variation and linear trends in annual temperatures (T_{max}, T_{min}, T_{mean}, and *DTR*) during T_1 (first non-global warming period; 1901–1909), T_2 (first global warming period; 1910–1945), T_3 (second non-global warming period; 1946–1975), and T_4 (second global warming period; 1976–2003) over Indian region. Values along the trend lines are the rate of change [°C (10 yr)$^{-1}$]. * 90% CL; ** 95% CL; and *** 99% CL. CL, confidence level.

The temperature trends observed during the second global warming period are significant at 99% CL.

[32] During the first non-global warming period, T_{min} is decreasing at a faster rate than T_{max} which in turn causes *DTR* to increase; whereas in the first global warming period, T_{min} is increasing at a slower rate than T_{max} which again causes *DTR* to increase (Figure 2). During the second non-global warming period, T_{max} is increasing; whereas, T_{min} is decreasing (−0.23°C (10 yr)$^{-1}$, significant at 99% CL) at a faster rate which causes *DTR* to increase (0.329°C (10 yr)$^{-1}$, significant at 99% CL) more rapidly. In the second global warming period, T_{min} is significantly increasing at a slower rate than T_{max} which again causes *DTR* to increase. Thus it has been observed that, during the analysis period (1901–2003; annual entry for *DTR* in Table 1) as well as in the non-global and global warming periods (Figure 2), *DTR* has increased.

[33] It has been observed that the significant cooling in T_{min} for the first (significant at 90% CL) and second (significant at 99% CL) non-global warming periods is mainly responsible for the actual decrease in annual T_{mean} during these periods; whereas, during the first/second global warming period, both T_{min} and T_{max} shows non-significant/significant warming due to which T_{mean} has increased non-significantly/significantly during this period.

4.2. Seasonal Trends

4.2.1. Winter

[34] The winter T_{mean} shows an increasing trend of 0.71°C (100 yr)$^{-1}$ significant at 99% CL, in spite of the decrease observed during the non-global warming periods (Figure 3). T_{max} and T_{min} also show significant warming during the analysis period as tabulated in DJF entries for T_{max} and T_{min} in Table 1.

[35] On close inspection, it has been observed that during the non-global warming periods T_{min} has decreased, whereas T_{max} shows warming tendency which in turn causes *DTR* to increase (Figure 3). In the global warming periods, T_{max} is increasing at a faster rate than T_{min} and hence causing *DTR* to increase. Since *DTR* shows an increasing tendency in all sub-periods therefore, its long-term trend also shows a significant increase (0.666°C (100 yr)$^{-1}$, significant at 99% CL); Mann-Kendall statistics also reveals the same.

4.2.2. Pre-monsoon

[36] The pre-monsoon T_{mean} also shows an increasing trend (0.402°C (100 yr)$^{-1}$), significant at 95% CL. Like winter, this increase is mainly attributed to the significant rise in T_{max} (0.629°C (100 yr)$^{-1}$, significant at 99% CL). T_{min} though shows an increase (0.174°C (100 yr)$^{-1}$), but is not statistically significant even at 90% CL.

[37] Like winter, T_{mean} and T_{min} for the pre-monsoon season also shows cooling/warming tendency during non-global/global warming periods, whereas T_{max} shows cooling tendency during the first non-global warming period and warming in rest of the other sub-periods (Figure 4).

[38] *DTR* neither shows an increasing nor decreasing tendency during the first non-global warming period, due to the equal cooling tendency shown by T_{max} and T_{min} (Figure 4). During the first global warming period, T_{min} is increasing at a faster rate than T_{max} which causes *DTR* to decrease. In the

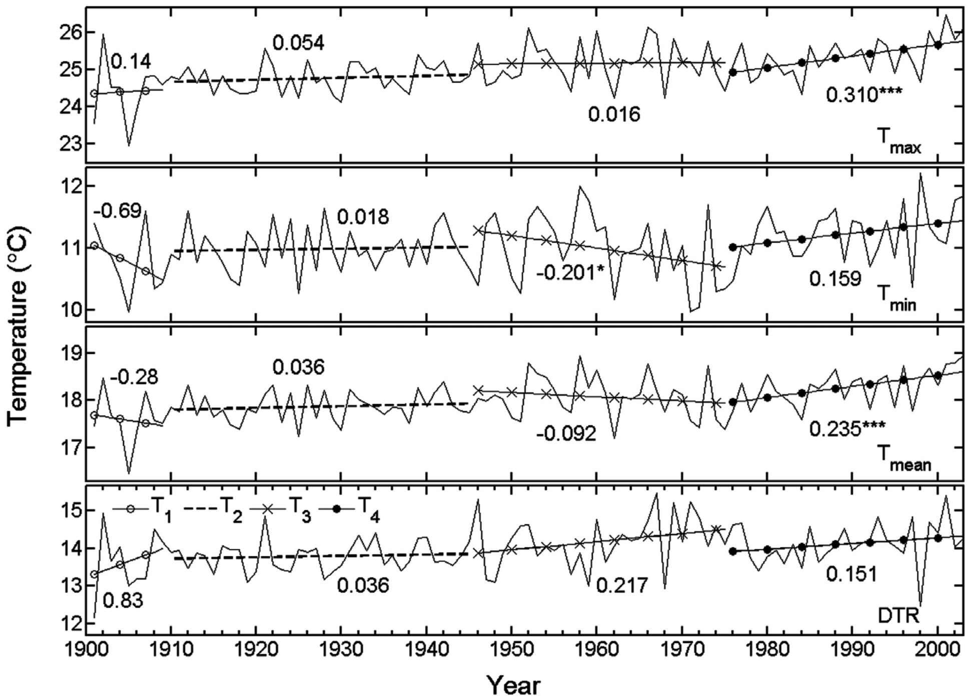

Figure 3. Variation and linear trends in winter (DJF) temperatures ($T_{\max}$, $T_{\min}$, T_{mean}, and DTR) during T_1 (first non-global warming period; 1901–1909), T_2 (first global warming period; 1910–1945), T_3 (second non-global warming period; 1946–1975), and T_4 (second global warming period; 1976–2003) over Indian region. Values along the trend lines are the rate of change [°C (10 yr)$^{-1}$]. * 90% CL; ** 95% CL; and *** 99% CL. CL, confidence level.

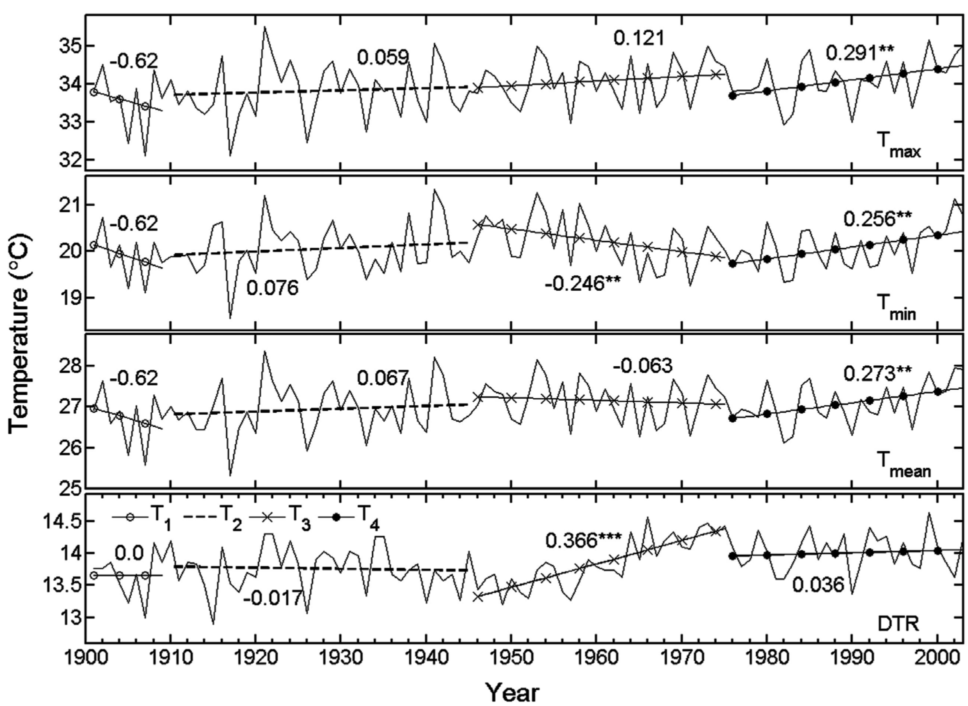

Figure 4. Variation and linear trends in pre-monsoon (MAM) temperatures ($T_{\max}$, $T_{\min}$, T_{mean}, and DTR) during T_1 (first non-global warming period; 1901–1909), T_2 (first global warming period; 1910–1945), T_3 (second non-global warming period; 1946–1975), and T_4 (second global warming period; 1976–2003) over Indian region. Values along the trend lines are the rate of change [°C (10 yr)$^{-1}$]. * 90% CL; ** 95% CL; and *** 99% CL. CL, confidence level.

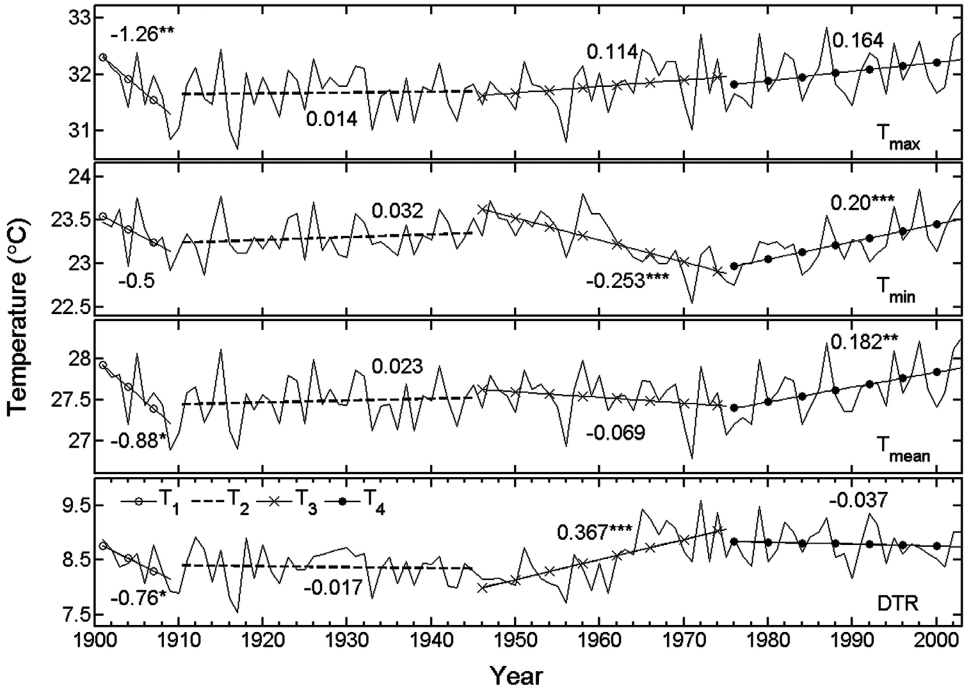

Figure 5. Variation and linear trends in monsoon (JJAS) temperatures ($T_{\max}$, $T_{\min}$, T_{mean}, and DTR) during T_1 (first non-global warming period; 1901–1909), T_2 (first global warming period; 1910–1945), T_3 (second non-global warming period; 1946–1975), and T_4 (second global warming period; 1976–2003) over Indian region. Values along the trend lines are the rate of change [°C (10 yr)$^{-1}$]. * 90% CL; ** 95% CL; and *** 99% CL. CL, confidence level.

second non-global warming period, $T_{\min}$ has significantly decreased (-0.246°C (10 yr)$^{-1}$, significant at 95% CL), whereas $T_{\max}$ shows warming (0.121°C (10 yr)$^{-1}$) tendency and hence causing DTR to increase (0.366°C (10 yr)$^{-1}$, significant at 99% CL). In recent decades i.e., during the second global warming period, $T_{\max}$ has increased (0.291°C (10 yr)$^{-1}$, significant at 95% CL), at a slightly faster rate than $T_{\min}$ (0.256°C (10 yr)$^{-1}$, significant at 95% CL) and causing a slight increase in DTR (not significant even at 90% CL).

4.2.3. Monsoon

[39] Like winter and pre-monsoon, T_{mean} for the monsoon season also shows an increasing trend of 0.182°C (100 yr)$^{-1}$, significant at 90% CL. This long-term increasing trend observed in T_{mean} is lowest and not highly significant among all seasons (entries for T_{mean} in Table 1) because for this particular season the long-term trend of $T_{\max}$ (entries for $T_{\max}$ in Table 1) is also lowest and $T_{\min}$ shows decreasing tendency (-0.1°C (100 yr)$^{-1}$, not significant even at 90% CL).

[40] Figure 5 shows the variation and linear trends in monsoon temperatures in the non-global and global warming periods. During the first non-global and second global warming periods, T_{mean} shows decreasing (-0.88°C (10 yr)$^{-1}$, significant at 90% CL) and increasing (0.182°C (10 yr)$^{-1}$, significant at 95% CL) trends; whereas in the first global and second non-global warming periods, the warming and cooling tendencies have been observed. In the first non-global/global warming period, DTR has significantly/non-significantly decreased because $T_{\max}$ is decreasing/increasing at a faster/slower rate as compared to $T_{\min}$. Whereas during the second non-global warming period, DTR has significantly increased due to the significant decrease in $T_{\min}$ and increase in $T_{\max}$. In the second global warming period, $T_{\max}$ is increasing at a slower rate than $T_{\min}$ and causing DTR to decrease.

4.2.4. Post-monsoon

[41] Like all seasons, T_{mean} for the post-monsoon season also shows an increasing trend of 0.849°C (100 yr)$^{-1}$, significant at 99% CL. Figure 6 shows that in the non-global and global warming periods, T_{mean} has increased. The increase in T_{mean} during the 2 non-global and first global warming periods is mainly attributed to the increase in $T_{\max}$ because in these periods $T_{\min}$ has decreased; whereas during the second global warming period, $T_{\max}$ is increasing at a much faster rate than $T_{\min}$ and hence contributing more toward the increase in T_{mean}.

[42] The long-term increasing trend (0.362°C (100 yr)$^{-1}$) is observed in DTR, but is not statistically significant even at 90% CL. In the non-global and first global warming periods, $T_{\max}$ is increasing while $T_{\min}$ is decreasing, which in turn causes DTR to increase; whereas during recent decades, $T_{\max}$ has significantly increased at a much faster rate as compared to $T_{\min}$ which again causes increase in DTR as shown in Figure 6.

4.3. Monthly Temperature Trends

[43] Table 2 shows the monthly long-term temperature ($T_{\max}$, $T_{\min}$, T_{mean}, and DTR) trends by subjecting them to the two-tailed Student's t-test and Mann-Kendall statistics. The highly significant increase in $T_{\max}$ has been generally observed for all months, except for May and June. February,

Table 2. Monthly Long-Term Temperature Trends (°C (100 yr)$^{-1}$) Over Indian Region During the Period 1901–2003[a]

Month	T_{max}	T_{min}	T_{mean}	DTR
Jan	0.5** (95%)	−0.114	0.193	0.613** (95%)
Feb	1.365*** (99%)	0.603** (95%)	0.984*** (99%)	0.761*** (95%)
Mar	0.736** (90%)	0.392* (90%)	0.564** (90%)	0.343
Apr	0.832*** (95%)	0.197	0.514*	0.635*** (99%)
May	0.32	−0.066	0.127	0.386** (95%)
Jun	0.235	−0.192	0.022	0.428* (90%)
Jul	0.413** (95%)	−0.073	0.17	0.486*** (95%)
Aug	0.526*** (99%)	−0.034	0.246*** (95%)	0.56*** (99%)
Sep	0.682*** (99%)	−0.102	0.29*** (99%)	0.784*** (99%)
Oct	0.767*** (99%)	0.325* (90%)	0.546*** (99%)	0.441
Nov	1.293*** (99%)	1.011*** (99%)	1.152*** (99%)	0.282
Dec	1.253*** (99%)	0.739*** (99%)	0.996*** (99%)	0.514* (95%)

[a]From Student's t-test: * 90% CL; ** 95% CL; and *** 99% CL. CL, confidence level. Trend's significance from Mann-Kendall statistics are given in parentheses.

November, and December months are the main contributors to the increase in annual T_{max}, since significantly higher increasing trends were observed for these months, whereas in case of T_{min}, all the months, except February–April and October–December are showing decreasing tendency. The significant increase in February, March, and October–December months are mainly causing the annual T_{min} to increase significantly at 95% (annual entry for T_{min} in Table 1).

[44] Like T_{max}, T_{mean} has also increased significantly, except in January and May–July in which warming tendency has been observed. In the month of November, the maximum change in T_{mean} has been observed due to significantly higher increase in T_{max} and T_{min}; whereas in the month

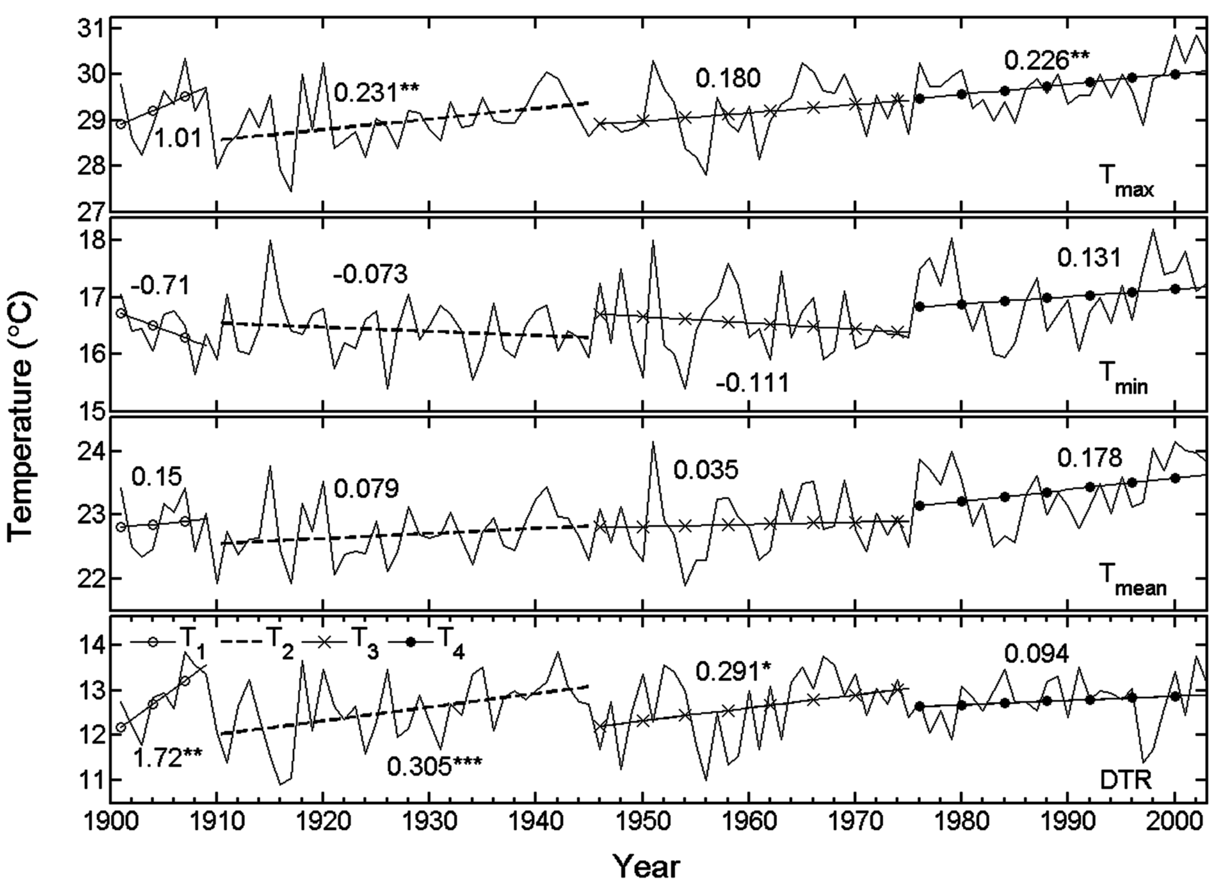

Figure 6. Variation and linear trends in post-monsoon (ON) temperatures (T_{max}, T_{min}, T_{mean}, and DTR) during T_1 (first non-global warming period; 1901–1909), T_2 (first global warming period; 1910–1945), T_3 (second non-global warming period; 1946–1975), and T_4 (second global warming period; 1976–2003) over Indian region. Values along the trend lines are the rate of change [°C (10 yr)$^{-1}$]. * 90% CL; ** 95% CL; and *** 99% CL. CL, confidence level.

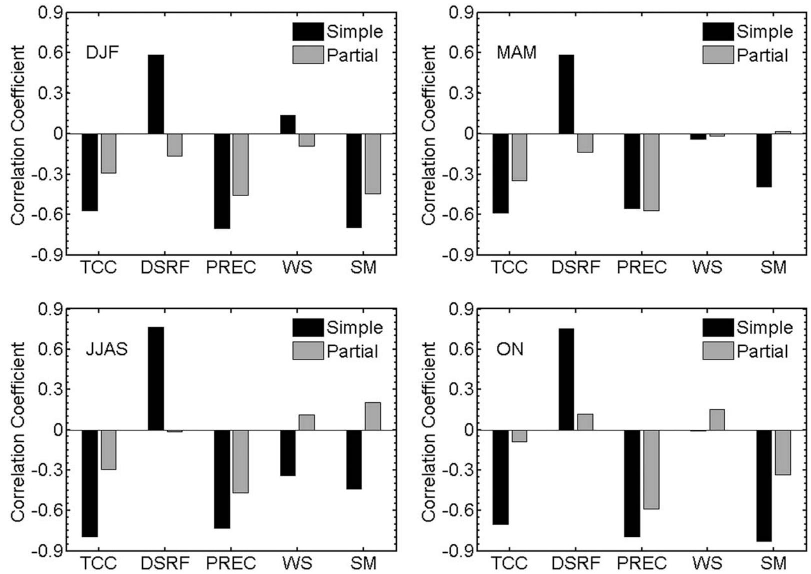

Figure 7. Simple and partial correlation coefficients between monthly *DTR* and total cloud cover (TCC), solar radiation downward (DSRF), precipitation (PREC), wind speed (WS), and soil moisture (SM) during winter (DJF), pre-monsoon (MAM), monsoon (JJAS), and post-monsoon (ON) over Indian region. Correlation coefficients larger (smaller) than 0.264 (−0.264) are statistically significant at 95% CL. CL, confidence level.

of June, the change in T_{mean} is negligible because the rate of increase in $T_{\max}$ is approximately equal to the rate of decrease in $T_{\min}$.

[45] In case of *DTR*, all the months are contributing significantly to the significant increase in annual *DTR*, except March, October, and November (increasing tendency). The maximum significant increase in *DTR* has been observed in September ($T_{\max}$ increased significantly, while $T_{\min}$ decreased) and in February ($T_{\max}$ is increasing at a much faster rate than $T_{\min}$) months while in March, October, and November only increasing tendency have been observed because $T_{\max}$ is increasing at a slightly faster rate than $T_{\min}$.

4.4. Factors Responsible for Change in *DTR* During the Period 1948–2003

[46] The surface energy balance and water conditions are the main factors responsible for the changes in *DTR* [*Liu et al.*, 2004; *Zhou et al.*, 2007]. Prior to perform the correlation analysis, the anomalies of each variable have been computed. Unless otherwise specified, the monthly values of each variable referred hereafter, in this section, are their respective anomalies. *DTR* was strongly anticorrelated with total cloud cover in monsoon and post-monsoon, similarly with precipitation in monsoon, post-monsoon, and winter and with soil moisture content in post-monsoon and winter (Figure 7). *DTR* was also firmly related with solar irradiance in all seasons; especially in monsoon and post-monsoon as shown in Figure 7. Thus it has been observed that, decrease (increase) in clouds along with the secondary damping effects from precipitation and soil moisture causes increase (decrease) in *DTR*, while an increase in solar irradiance will cause it to increase and vice versa.

[47] Thus on the basis of these correlations and some physical perceptive (e.g., surface sensible and latent heat fluxes may be affected by wind speed which in turn affects surface temperatures [*Dai et al.*, 1999]; presence of clouds reduces the solar radiant energy reaching the Earth's surface which again in turn affects the $T_{\max}$ and $T_{\min}$; etc.), partial correlation coefficients of these variables with *DTR* were calculated, in order, to get rid of the effects on *DTR* of the interaction among variables. For this, the monthly *DTR* was linearly regressed on the following variables: total cloud cover, precipitation, solar irradiance, surface wind speed, and top 10-cm soil moisture content, and finally the partial correlation coefficients were computed on this model by excluding one variable each time.

[48] Among all the variables, total cloud cover (for all seasons, except post-monsoon), precipitation (for all seasons), and soil moisture content (for the post-monsoon and winter seasons) have the strongest partial correlation with *DTR*, significant at 95%. The simple and partial correlation coefficients, shown in Figure 7, between monthly *DTR* and rest of the other variables clearly depicts that among all the variables, total cloud cover and precipitation account for the largest amount of *DTR* variance.

[49] In post-monsoon and winter seasons, soil moisture is anticorrelated with *DTR*, even after removing the effects of the other variables, signifying that soil moisture also

Table 3. Correlation Between Total Cloud Cover (TCC) and Temperatures ($T_{\max}$, $T_{\min}$, and *DTR*) Over Indian Region During the Period 1948–2003[a]

Season	TCC-$T_{\max}$	TCC-$T_{\min}$	TCC-*DTR*
DJF	−0.249	**0.411**	**−0.572**
MAM	**−0.401**	−0.05	**−0.589**
JJAS	**−0.737**	0.053	**−0.792**
ON	**−0.296**	**0.434**	**−0.702**

[a]Values in boldface are statistically significant at 95% CL. CL, confidence level.

Table 4. Seasonal Trend of Total Cloud Cover (TCC), Precipitation (PREC), Soil Moisture (SM), *DTR*, and Downward Solar Radiation Flux (DSRF) Over Indian Region During the Period 1948–2003[a]

Season	TCC	PREC	SM	DTR	DSRF
DJF	−11.82***	6.05	8.23e-004	0.37	13.67***
MAM	−19.20***	1.39	−5.87e-003	0.89***	30.16***
JJAS	−10.06***	−27.71	7.3e-003	1.08***	19.87***
ON	−7.65**	−4.63	−5.64e-003	0.79	11.18*

[a]Trends are given in (100 yr)$^{-1}$. From Student's t-test: * 90% CL; ** 95% CL; and *** 99% CL. CL, confidence level.

modulates *DTR* and whose effect on *DTR* cannot be accounted for by the changes in total cloud cover, precipitation, solar irradiance, and winds. This is physically consistent with the idea that the soil moisture provides moisture for evaporation due to which the part of the solar radiation energy hitting the Earth's surface is used to evaporate the water in the soil instead of heating the ground and subsequently the air that results in less boundary layer warming than expected (evaporative cooling effect) which basically limits $T_{\max}$, whereas its effect on $T_{\min}$ is negligible that causes decrease in *DTR*.

[50] The correlations between total cloud cover and $T_{\max}$ or $T_{\min}$ (Table 3) reveals that $T_{\max}$ anticorrelates strongly with total cloud cover in monsoon and pre-monsoon season, while the total cloud cover and $T_{\min}$ correlation is very weak for monsoon (0.053) and pre-monsoon (−0.05) seasons.

[51] These correlations, shown in Figure 7 and those tabulated in Table 3, do not actually represent the relationships among the variables from the real world. There might be some uncertainties in these correlations because both the temperature and the precipitation are 'observed' variables, while the rest are the 'model estimated' variables from NCEP/NCAR reanalysis project.

[52] From 1948 to 2003 the total cloud cover over India is decreasing in all seasons (entries for TCC in Table 4) and is highly anticorrelated with $T_{\max}$ in monsoon and pre-monsoon (Table 3) which will tend to increase $T_{\max}$, whereas its net effect on $T_{\min}$ is relatively small during these warm seasons because clouds reflect sunlight, which reduces afternoon temperatures and thus subsequently $T_{\min}$, but it also enhances downward longwave radiation which increases $T_{\min}$ [*Dai et al.*, 1999] which in turn causes maximum increase in *DTR* in these two seasons (entries for MAM and JJAS for *DTR* in Table 4).

[53] In monsoon season, the partial correlation between the primary (secondary) factor i.e., cloud (precipitation) and *DTR* is −0.294 (−0.466), signifying that decrease in clouds (precipitation) will tend to increase *DTR* and vice versa. Entry of JJAS for TCC (PREC) in Table 4 clearly demonstrates that clouds (precipitation) shows significant/non-significant decreasing trend which will enhance *DTR*. Since, both clouds and precipitation provides positive feedback that is why a maximum significant increasing trend (entry of JJAS for *DTR* in Table 4) has been observed in *DTR* for the monsoon season.

[54] In pre-monsoon season, both total cloud cover and precipitation is significantly anticorrelated with *DTR*, having partial correlation coefficients −0.348 and −0.574, and showing significant decreasing and non-significant increasing trends (entries for MAM for TCC and PREC in Table 4) which will tend to increase and decrease *DTR*. Thus, as compared to monsoon (in which both clouds and precipitation are providing the positive feedback) season a little lower but significant increasing trend has been observed in pre-monsoon season (entry of MAM for *DTR* in Table 4).

[55] In winter season, total cloud cover (precipitation/soil moisture) shows significant decreasing trend (increasing/slight-increasing tendency) and having a partial correlation coefficient of −0.293 (−0.459/-0.444) signifying that it provides positive (negative/negative) feedback which will enhance (decrease/decrease) *DTR*. As a result, a minimum non-significant change in *DTR* has been observed during the period 1948–2003; whereas its long-term (1901–2003) trend is maximum for winter as compared to rest of the other seasons.

[56] For the post-monsoon season, the negatively weak partial correlation of *DTR* with total cloud cover has been observed (Figure 7), signifying that for this season the effect of decreasing clouds in increasing *DTR* is not as high as compared with warm seasons. That is why a weak non-significant increasing tendency (entry of ON for *DTR* in Table 4) has been observed in *DTR* during the period 1948–2003. Besides this, the other factors like solar irradiance (increasing significantly; partial correlation 0.116 with *DTR*), precipitation (decreasing tendency; partial correlation −0.586 (significant at 95%)), and soil moisture (slightly decreasing; partial correlation of −0.336 (significant at 95%)) provides positive feedback to *DTR*, along with clouds that tends to enhance *DTR*.

5. Conclusion

[57] In this paper we have explored the annual, seasonal, and monthly long-term trends in surface air temperature ($T_{\max}$, $T_{\min}$, T_{mean}, and *DTR*) over India during the period 1901–2003. Additionally, the annual and seasonal trends are also examined in the two non-global and global warming periods defined by IPCC. Besides this, the possible factors responsible for the increase in *DTR* during the period 1948–2003 are also scrutinized.

[58] The urbanization plays a crucial role in the analysis of long-term temperature change because it directly affects the surface air temperature's trend. The urbanization and changing land-use have been acknowledged as factors that influence $T_{\min}$. The reason behind this is the high consumption of energy and friction in cities due to which the significant amount of waste heat gets stored in the walls of buildings and streets. This waste heat gets released during the night and thereby making the night warmer [*Gadgil and Dhorde*, 2005]. Therefore, there is a need to check and remove its effect before studying the regional or global average surface air temperature [*Karl et al.*, 1988; *Jones et al.*, 1990; *IPCC*, 2001; *Hansen et al.*, 2001; *Zhou et al.*, 2004]. But, examining the impacts of urbanization/land-use change on mean surface temperature calculations is a challenging task. However, many places around the observatory are rapidly urbanized over a period of time and due to that there may be some in-homogeneity in the data records. However, there is hardly any practical approach to account these changes in the data. This might be the limitation of the

present study in which the effect of urbanization has not been taken into account, while doing the analysis of long-term temperature change over India.

[59] Compared with the previous studies [*Kumar et al.*, 1994; *Kothawale and Rupa Kumar*, 2005] the points on which the present study are consistent, different, and supersedes them are discussed in the following paragraphs along with the probable reason of any discrepancy, if observed.

[60] In the present study, the lengthened data for the period 1901–2003 has been used as compared to that used by *Kumar et al.* [1994], i.e., 1901–1987. The main outcomes of the present study is that $T_{\min}$ has increased significantly (95% significant) during the period 1901–2003. This is in contradiction to *Kothawale and Rupa Kumar* [2005], while *Kumar et al.* [1994] reported that during 1901–1987, $T_{\min}$ is trendless. The accelerated and the significant warming of $T_{\min}$ during the recent decades might be the plausible cause of its overall significant increase.

[61] One of the important findings of the present study is that the annual temperatures (T_{mean}, $T_{\min}$, and $T_{\max}$) show a cooling/warming tendency during the non-global/global warming periods, except in the second non-global warming period of $T_{\max}$. The seasonal trends observed in $T_{\min}$ and T_{mean} also shows cooling/warming tendency during the non-global/global warming periods, apart from the first (first and second) global (non-global) warming period of $T_{\min}$ (T_{mean}) for the post-monsoon season; whereas $T_{\max}$ shows warming during all sub-periods, excluding the first non-global warming period for the pre-monsoon and monsoon seasons. No such type of analysis has been done in any of the previous studies.

[62] In this study it has been found that $T_{\min}$ is statistically significant in post-monsoon and winter season, while *Kumar et al.* [1994] reported that $T_{\min}$ is not statistically significant in any of the seasons during the period 1901–1987. The present study shows that the increase in $T_{\max}$ is high and statistically significant in all seasons, while *Kumar et al.* [1994] stated that $T_{\max}$ is high and statistically significant in all seasons, except the monsoon. The present study exemplifies that T_{mean} increased in all seasons, with largest increase in post-monsoon and winter; as both $T_{\max}$ and $T_{\min}$ shows greatest increase in these two seasons. This clearly depicts that, both post-monsoon and winter seasons are getting warmer in regards of $T_{\max}$ and $T_{\min}$.

[63] Besides this, in the present study *DTR* has been analyzed on annual, seasonal, and monthly basis; whereas, *Kumar et al.* [1994] examined it only on annual basis. During the analysis as well as in the non-global and global warming periods, annual *DTR* has increased. *DTR* showed detectable changes in all seasons, with the fastest increase in winter ($T_{\max}$ is increasing at a much faster rate than $T_{\min}$) and slowest in post-monsoon (less asymmetry between $T_{\max}$ and $T_{\min}$). Monthly analysis of *DTR* reveals that all the months are contributing significantly to the increase in annual *DTR*, except March, October, and November in which warming tendency has been observed. The maximum significant increase in *DTR* has been observed in September ($T_{\max}$ increased significantly, while $T_{\min}$ has decreased) and in February ($T_{\max}$ is increasing at a much faster rate than $T_{\min}$) months.

[64] In addition to this, the plausible factor (s) responsible for the increase in *DTR*, during the period 1948–2003, are also investigated. None of the previous studies have tried to investigate it over the Indian region. In monsoon season, both clouds and precipitation provides positive feedback that is why a maximum significant increasing trend has been observed in *DTR* for the monsoon season; whereas in pre-monsoon season, only clouds provide positive feedback. In winter season, clouds (precipitation/soil moisture) provide positive (negative/negative) feedback which results a minimum non-significant change in *DTR*; whereas for the post-monsoon season, the negatively weak partial correlation of *DTR* with total cloud cover has been observed, suggesting that for this season the effect of decreasing clouds in increasing *DTR* is not as high as compared with warm seasons. Thus, total cloud cover along with secondary factors like precipitation and soil moisture emerged to be the probable cause of the increase in *DTR* over India during the period 1948–2003. The change in *DTR* is significantly anticorrelated with the changes in total cloud cover and precipitation, predicting these two climatic variables as key factors to the increase in *DTR*.

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