Spatio-temporal changes in temperature over India

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A study was taken up to identify annual changes in temperature at a scale of 1° × 1°. For this study, daily (maximum and minimum) temperature data for 45 years (1969–2013) at a grid size of 1° × 1°, prepared by the India Meteorological Department, Pune were used. The identification of change was based on statistical trend analysis. From the analysis, it can be concluded that the dominant tendency over the India land mass is of warming, and colder months of the year show more warming. Analysis of temperature difference (TD) brought out the existence of contiguous and large spatial clusters of shrinking and expanding TD. Further analysis is required to factor the variability in temperature due to anthropogenic changes.

Keywords: Annual changes, spatio-temporal patterns, temperature difference, trend analysis.

SURFACE air temperatures are rising globally[1]. However, the warming is not uniform in space and across seasons. With this in mind, analysis of temperature variability and change at a grid size of 1° × 1° was carried out. Monitoring annual changes at such a scale is required for deciding adaptation and mitigation measures to satisfy the needs of the projected population.

Several researchers have studied annual variations in temperature in different parts of the world[2–7]. They have resorted to parametric and non-parametric statistical analysis to identify and quantify the magnitude of these changes. In India, as early as in 1950s, trends in the maximum temperature (T_{max}), minimum temperature (T_{min}) and average temperature (T_{avg}) over the whole country have been studied[8], but no general tendency was observed. Based on analysis of station data for 1901–1987, it was concluded that T_{max}, and hence T_{avg}, increases over most parts of India, particularly in post-monsoon and winter seasons[9]. Rising trend was confirmed in T_{max} and T_{avg} (ref. 10). Warming trend in monsoon temperatures (T_{max} and T_{min}) was observed leading to weakened season asymmetry of temperature reported earlier[9]. Analysis of temperature data revealed generally rising trend in South, Central and West India and declining trend in North and North East India in T_{max} and mixed response in T_{min} (ref. 11). Inconsistent climatic response to urbanization was reported[12]. Trends in temperature during different seasons and over different regions as well as extremes of different intensities and duration in India have also been reported[13,14].

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The daily gridded dataset for T_{max} and T_{min} was obtained from India Meteorological Department (IMD), Pune. It consists of consistent set of gridded data based on observations collected from 395 stations[15]. With the availability of data at finer spatial scale of 1° × 1° and temporal scale of a day, the study was conducted to identify patterns of changes at annual timescale. The data were available for 45 years. Also, it is well reported that average temperature is a key indicator of climate change[4,16,17]. Anthropogenic activities reduce temperature differences[17–22]. Therefore average temperature, defined as $T_{avg} = [(T_{max} + T_{min})/2]$, and temperature difference, defined as $TD = (T_{max} - T_{min})$ were also analysed. It is well known that there is a systematic behaviour of temperature within a year with summer temperatures being warmer and winter temperatures being cooler. To avoid the seasonal pattern in temperature, the data were analysed month-wise.

Temperature was modelled as a function of time to detect and identify a pattern. This was done using a parametric linear trend analysis technique. In this approach, a least square linear trend of the form '$a + b$*year' was fitted for each grid. The parameters of the fit such as coefficients, their standard errors, R^2 value and F-statistic were also computed. The statistical significance of the estimated change was determined. If there is an increasing (decreasing) trend in the series, then the slope coefficient will be positive (negative) and statistically significant. All the statistical testing was done at 5% significance level.

Temporal analysis was performed for each grid. For a given grid and a given day, a temperature series can be formed. If a study area is covered by N grids and there are 365 days of a year, then there are $365*N$ series to be evaluated. Grid-days are defined as the product of number of grids and number of days. Grid-days are combine spatial (no. of grids) and temporal (no. of days having statistically significant change) extent. For example, for an area covered by N grids, if Y grid-days indicate statistically significant change days, then we can say that, on an average, the region experienced change on (Y/N) days. Thus grid-days are a joint indicator of persistence and amount of change.

For each grid, the average slope, defined as sum of all statistically significant slopes divided by the number of such days, was calculated. The summation was carried over a month or year, as the case may be.

From the analysis of annual patterns in daily temperature data at 1° × 1° resolution, grid-days having statistically significant changes in all the four temperature variables during 1969–2013 were calculated. Table 1 gives the number of grid-days undergoing change during a month. From the last two rows of Table 1, it can be seen that warming is dominant in T_{min} [17341/(17341 + 731) > 95%], T_{avg} [14077/(14077 + 595) >95%)] and T_{max} [12922/(12922 + 1554) > 89%].

Table 1. Monthly grid-days in annual changes in four temperature variables during 1969–2013 of India during various months

Season	Month	Category	T_{max}	T_{min}	T_{avg}	TD
Winter	January	Increase	1842	930	1237	698
		Decrease	1150	68	360	1585
	February	Increase	1702	1529	1749	786
		Decrease	1	126	21	579
Pre-monsoon	March	Increase	1380	1660	1322	682
		Decrease	0	135	40	631
	April	Increase	197	466	276	385
		Decrease	38	85	6	407
	May	Increase	411	1209	752	307
		Decrease	2	58	16	290
Southwest monsoon	June	Increase	240	835	402	145
		Decrease	8	28	11	170
	July	Increase	587	1819	905	249
		Decrease	61	64	62	374
	August	Increase	972	2278	1397	441
		Decrease	11	68	7	172
	September	Increase	852	2348	1215	369
		Decrease	42	77	19	474
Post-monsoon	October	Increase	371	1231	687	86
		Decrease	60	16	48	371
	November	Increase	1571	1147	1479	159
		Decrease	17	4	0	832
	December	Increase	2797	1889	2656	285
		Decrease	164	2	5	1141
Annual		Increase	12922	17341	14077	4592
		Decrease	1554	731	595	7026

TD, Temperature difference.

Figure 1 provides a spatial representation of distribution of average slope in four temperature variables. It can be seen that warming over the Indian landmass is dominant. A critical look at the Figure 1 *a–c* indicates noticeable patterns of warming in Jammu and Kashmir (J&K), western Rajasthan, Madhya Pradesh and North East India. It is seen that there is an increase in T_{max} in all regions, except the Indo-Gangetic Plains (IGP) and Sikkim. Similarly, T_{min} is increasing all over, except the region bordering Odisha and Chhattisgarh. The same pattern is replicated in T_{avg}. The most surprising feature is seen in TD, where clear spatial cluster of shrinking and expanding TD emerges.

Table 2 gives the category-wise distribution and region covered by these types of changes in average temperature. It can be seen from Table 2 that 325 (192 + 137) grid cells have dominance of warming, whereas 12 (5 + 7) grid cells represent dominance of cooling suggesting overall warming of the Indian land mass. It can be seen that 192 grid cells have increase only compared with only five grid cells which have cooling only. Of the 197 grid cells having warming only, 22 have warming for more than 90 days these are mostly at the tip of peninsular India, South of NE India and north part of Gujarat coast. Figure 2 gives its spatial distribution. The legend has three components, namely colour, class description and the number within brackets indicates count of grid cells that belong to this category.

From the bottom two rows of Table 1, it can be seen that annual trend of warming is dominant in T_{min} (>95%), T_{avg} (>95%) and T_{max} (>89%). This is in contrast to earlier observations[9,10] T_{max} was changing much more in comparison with T_{min}. This was attributed to land-use changes and increased aerosols in the atmosphere. The present analysis reveals that T_{min} is also increasing. This could be due to effects of anthropogenic activities and increasing level of greenhouse gases in the atmosphere.

Critical look at IGP in Figure 1 reveals that T_{max} is decreasing and T_{min} is showing warming. However, warming of T_{min} is more compared to lowering of T_{max} and the net result is mild warming as can be seen in T_{avg}. It is interesting to note (refer Table 1) that the season from November to March, with the exception of January, shows predominant and large-scale warming. This period corresponds to colder months. Exclusion of January is difficult to explain. However, it is well reported that a combination of meteorological conditions (low ambient temperature, high relative humidity and low winds), smooth topography and ground situation (vegetated cover, elevated levels of aerosols due to biomass burning)

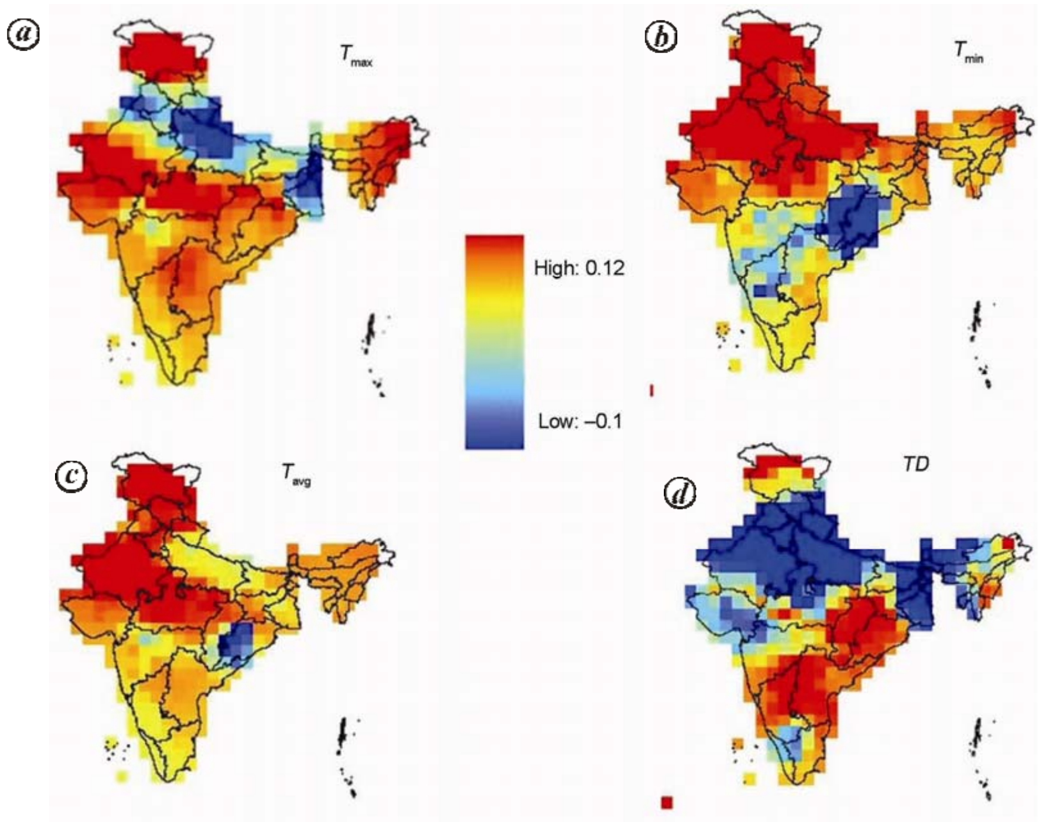

Figure 1. Spatial depiction of annual average slope in (***a***) T_{max}, (***b***) T_{min}, (***c***) T_{avg}, (***d***) TD.

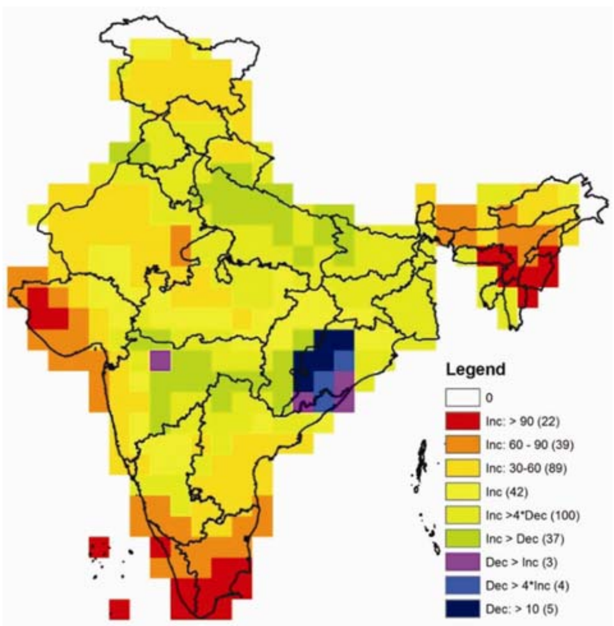

Figure 2. Distribution of category-wise change in average temperature (T_{avg}).

during December and January favours formation of fog in the Indo-Gangetic belt[23–28]. The number of foggy days is found to be increasing in the recent past[29,30]. Combined effect of fog and pollution results in lowering of T_{max} (ref. 31). Moisture in the atmosphere, low insolation reaching ground and latent heat component of energy balance combinly act to form a radiative feedback mechanism which may be the reason for exclusion of January (and to some extent December) from the typical behaviour of cooler months. This can be seen from images of average slopes for T_{max}, T_{min} and T_{avg} for December–February (Figure 3).

TD reflects joint variability due to cloudiness, soil moisture, humidity and atmospheric circulation pattern. Land-use changes due to availability of irrigation facility as well as of increased aerosols in the atmosphere due to industrialization are probably causing warming of the Indian landmass. However, contiguous and large spatial clusters of shrinking and expanding TD that emerge (Figure 1 *d*) are not well understood. The region of shrinking TD is the irrigated part of northwest India, the wheat belt of the country. Due to availability of irrigation (and hence soil moisture), wheat is grown as a cash crop in winter. There may be other anthropogenic factors such as increased aerosol loading due to transportation, urbanization and industrialization which contribute to this phenomenon. Further analysis is required to explain and factor the spatio-temporal variability in temperature to anthropogenic changes such as land-use changes, increased aerosols and air pollution. These hypotheses need to be investigated further and confirmed.

Table 2. Distribution of grid cells based on various categories of change in average temperature (T_{avg})

Category	Grid cells		Sub-category	Region
Increase only	192	22	More than 90 days	Tip of peninsular India; South of North East India (NEI); north part of Gujarat coast
		39	60–90 days	Neighbouring region above and north of west coast
		89	30–60 days	J&K; Western Rajasthan; south Andhra Pradesh; remaining part of NEI
		42	Less than 30 days	Parts of Central India (CI)
Increase dominating	137	100	Increase more than four times decrease	Most part of Indo-Gangetic Plain (IGP) except foothills of Himalaya in Uttrar Pradesh and Bihar
		37	Increase more than decrease	Remaining part of IGP and CI
Decrease dominating	7	3	Decrease more than four times increase	Odisha and Chhattisgarh border
		4	Decrease more than increase	Odisha and Chhattisgarh border
Decrease	5	5	Decrease more than 10 days	Odisha and Chhattisgarh border
		0	Decrease	

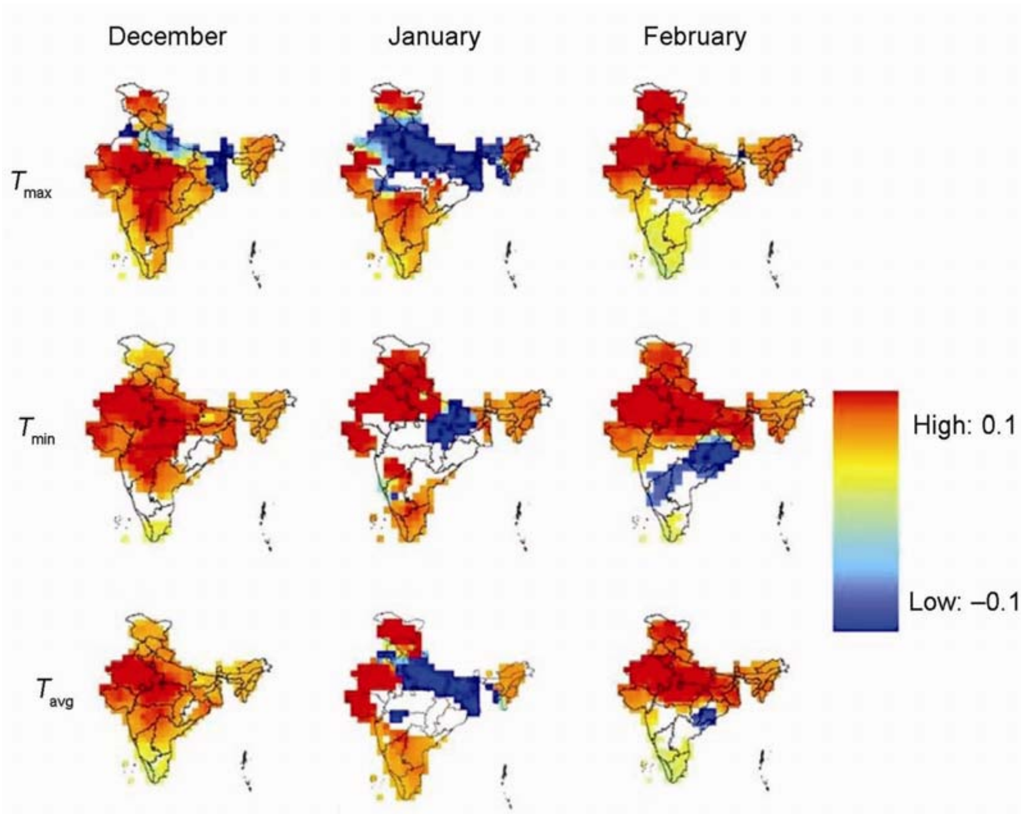

Figure 3. Spatial depiction of monthly average slope in T_{max}, T_{min} and T_{avg} during December–February.

There are 39 cells with warming of 60–90 days (refer Table 2) which are in the neighbouring region of the above (with >90 days of warming only) category. Most parts of Kerala and Tamil Nadu are occupied by these two categories of intense warming. There are 89 cells having warming for 30–60 days which lie in J&K, western Rajasthan, south Andhra Pradesh and the remaining region of NE India. It can be seen that Tamil Nadu, Kerala and NE India show widespread and intense warming. There are 42 grid cells where there is warming only and they lie in parts of Central India. There are 137 grid cells representing warming dominance. Of these, 100 grid cells are such that warmer days are more than four times cooler days, mostly in the foothills of the Himalaya in Uttar Pradesh and Bihar – fog-prone region in the months of December and January. Most of the five cooling-only grid cells and 7 grid cells having cooling dominated over warming are in south Odisha and bordering Chhattisgarh

(Figure 2). This region shows decreasing trend in T_{min} and T_{avg} (refer Figure 1 *b* and *c*). It is known that this region has good forest cover with less urbanization and industrial development. It is probably unaffected by anthropogenic factors.

From the analysis of 45 years of daily gridded temperature data over the Indian land mass, it can be concluded that: (i) the dominant tendency is of warming; (ii) regionwise, Tamil Nadu, Kerala and NE India show widespread and intense warming; (iii) area bordering Odisha and Chhattisgarh shows cooling trend, and (iv) colder months of the year (February, December and November) show more warming and warmer months (May–July) show very little warming. However, contiguous and large spatial clusters of shrinking and expanding TD that emerge are not well understood. Further analysis is required to explain and factor the spatio-temporal variability in temperature to anthropogenic changes such as land-use changes, increased aerosols and air pollution.

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