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On the recent changes in surface temperature trends over India

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[1] Marked differences from global trends in terms of diurnal asymmetry of temperature trends were reported earlier for India, indicating that the warming over India was solely contributed by maximum temperatures. We report substantial recent changes in the nature of trends, using updated data sets up to 2003, with special focus on the last three decades. While all-India mean annual temperature has shown significant warming trend of 0.05°C/10yr during the period 1901–2003, the recent period 1971–2003 has seen a relatively accelerated warming of 0.22°C/10yr, which is largely due to unprecedented warming during the last decade. Further, in a major shift, the recent period is marked by rising temperatures during the monsoon season, resulting in a weakened seasonal asymmetry of temperature trends reported earlier. The recent accelerated warming over India is manifest equally in daytime and nighttime temperatures.

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1. Introduction

[2] The monitoring and analysis of atmospheric temperatures on global as well as regional scales has acquired special importance in the last few decades due to the clear indications of global warming in the post-industrial era. The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) concluded that the global mean surface air temperature has increased by 0.6°C during the 20th century [*Intergovernmental Panel on Climate Change*, 2001]. Considerable emphasis has also been placed on the manifestation of regional warming/cooling in terms of daytime and nighttime temperatures, because of their links to the changes in cloudiness, humidity, atmospheric circulations patterns, wind and soil moisture [*Karl et al.*, 1993]. *Easterling et al.* [1997] reported that the temperature range between daytime high temperature and night time low temperature decreased for most part of world during the period 1950–1993.

[3] In one of the earliest studies for the Indian region in the context of contemporary global warming, *Hingane et al.* [1985] reported that the mean annual temperature increased by about 0.4°C/100yr in India during 1901–82. *Rupa Kumar et al.* [1994] pointed out that, while the mean temperature trends over India were similar to the global and hemispheric trends, the diurnal asymmetry of surface temperature trends observed over India is quite different from that in the other parts of the world [*Karl et al.*, 1993]. The increase in the mean temperature over India was almost solely contributed by maximum temperatures, with the minimum temperature remaining practically trendless. In a recent study, *Krishnan and Ramanathan* [2002] have brought out that the all-India surface air temperature during the drier part of the year (January–May) has been subject to a relative cooling by as much as 0.3°C during the last three decades, when the global effects of greenhouse gases and natural variability are filtered out from the temperature series. However, it must be pointed out here that, this is rather a perceived cooling, and the overall temperature trends still indicate significant warming, presumably due to a predominance of greenhouse forcings. *Kothawale and Rupa Kumar* [2002] have reported significant post-1970 warming in the lower troposphere over India. In the context of unprecedented changes in global/hemispheric temperatures [*Jones and Moberg*, 2003] and the possible signatures of anthropogenic impacts, the present study updates the data sets for the region, and reports characteristic changes in the temperature trends both in terms of seasonal and diurnal asymmetry.

2. Data and Analysis

[4] Monthly temperature data used in the present study, over a network of 121 stations (Figure 1), are the same as those used by *Pant and Rupa Kumar* [1997] for the period 1901–1990, which were originally sourced from the monthly weather records of the India Meteorological Department (IMD). The data have then been updated for the period 1991–2003 from the Indian Daily Weather Reports (IDWRs) published by the IMD. However, it may be noted here that the network during the updated period contains substantially less number of stations. Detailed checks made by degrading the earlier data to less density indicate that the network density in the recent period adequately represents the large-scale temperature variability over the regions considered in the present study. To identify the regional patterns of temperature variation within country, annual and seasonal winter (DJF), pre-monsoon (MAM), monsoon (JJAS) and post-monsoon (ON) temperatures series have been constructed for all-India and seven homogeneous regions, viz., Western Himalaya (WH), Northwest (NW), North Central (NC), Northeast (NE), West Coast (WC), East Coast (EC) and Interior Peninsula (IP) for the period 1901–2003 (Figure 1). These regions are demarcated based on geographical, topographical and climatological features.

[5] In order to project a more realistic temperature climatology onto the limited data used in the present study, climatological normals of monthly mean maximum and minimum temperatures for the period 1951–80 for 388 well-spread stations have been taken from *India Meteorological Department* [1999]. To prepare spatially well-representative means of temperatures for the above-mentioned homogeneous regions, the following procedure

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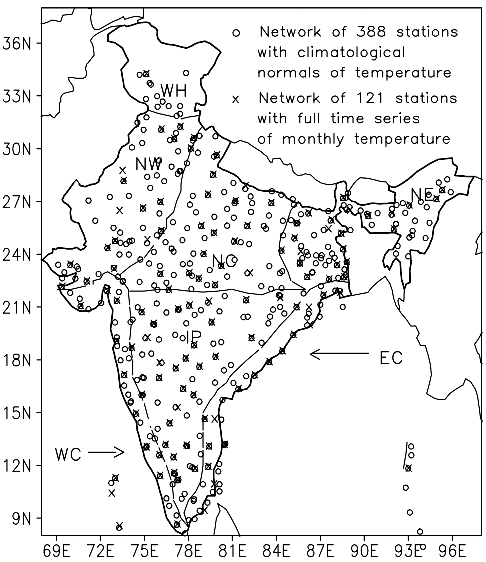

Figure 1. Network of temperature stations and homogeneous regions used in the study.

has been adopted. The available station temperature data have been converted to monthly anomaly time series for the period 1901–2003, with reference to the respective station normal values. The stationwise monthly temperature anomaly time series are first objectively interpolated onto a $0.5^\circ \times 0.5^\circ$ grid for the entire period of 1901–2003. Then, the climatological normals (1951–80) of temperature at 388 stations have been interpolated onto the same grid, resulting in high-resolution grid point temperature climatology for the country. The gridded monthly anomaly values are then added to the gridded climatology based on 388 stations, finally producing a long-term gridded data set of actual temperatures for India for the period 1901–2003. All-India and regional monthly temperature series are computed by simple averages of the constituent grid point data of the respective regions.

[6] The trend is quantified by the slope of a simple linear regression line fitted to each of the series against time. The statistical significance of trend is assessed by means of the F-ratio, after taking into account the autocorrelation, if any, present in the series [*Wigley and Jones*, 1981].

3. Results and Discussion

[7] All-India mean annual temperature shows significant warming trend of 0.05°C/10yr during the period 1901–2003 and 0.22°C/10yr during recent period 1971–2003 (Figure 2). This represents a substantial acceleration of the warming during the last three decades. The warming trend in annual mean temperature during 1901–2003 is mainly contributed by significant warming of annual maximum temperature (0.07°C/10yr) while the annual minimum temperature remains trendless (Table 1). However, during the recent period 1971–2003, the significant warming trend in mean annual temperature is contributed by both maximum (0.2°C/10yr) and minimum temperatures (0.21°C/10yr). This feature is a major turn-around in the diurnal asymmetry of temperature trends over India reported by *Rupa Kumar et al.* [1994].

[8] The temperature series are also marked by considerable decadal variability (Figure 2). While the maximum temperatures in the 60s are higher than the following decades, the minimum temperatures during the 60s through 80s are below normal. However, both the temperatures show unprecedented warming in the late 90s and later. The trends during 1960–94 in all the temperature series are not statistically significant, but those for the period 1960–2003 exceed 0.11°C/10yr and are highly significant, though substantially less than the trends during 1971–2003. Thus, the recent accelerated warming seems to have commenced in 1971, and is exacerbated by the surge in temperatures during the last decade, which has also been seen in the sub-regional mean temperatures (not shown). Indeed, even the global mean temperatures attain their peak values in the late 90s and later period [*Jones and Moberg*, 2003]. While the diurnal temperature range shows significant increasing trend for the period 1901–2003, it is practically trendless over the past three decades as a consequence of increasing minimum temperatures (Figure 2).

[9] In terms of the areal extents of significant trends, the country is predominantly under a warming regime with the winter season showing the most extensive warming (Table 2). However, the seasonal asymmetry in the trends seems to be weakening in the recent period, with the monsoon temperatures showing significant increases over a relatively large area, which is most conspicuous in the case of minimum temperatures.

[10] During the period 1901–2003, all-India maximum temperature shows significant warming trend in all the seasons, whereas during the recent period 1971–2003, only

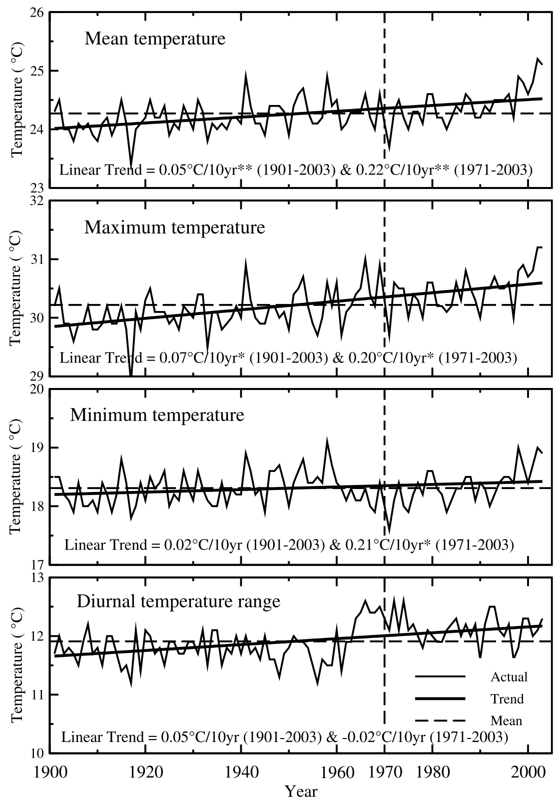

Figure 2. Variation of all-India mean, maximum, and minimum temperatures during 1901–2003 (* Significant at 5% level; ** Significant at 1% level).

Table 1. Linear Trend (°C/10yr) in Maximum and Minimum Temperatures for All-India and Homogeneous Regions

		1901–2003					1971–2003				
Region	Temp	DJF	MAM	JJAS	ON	Annual	DJF	MAM	JJAS	ON	Annual
All-India	Max	0.10[b]	0.06[a]	0.05[a]	0.10[b]	0.07[a]	0.27[b]	0.14	0.16	0.30[a]	0.20[a]
	Min	0.04[a]	0.02	−0.01	0.07[a]	0.02	0.28[a]	0.17	0.20[b]	0.24	0.21[a]
Western Himalaya	Max	0.16[a]	0.10	0.04	0.09	0.09[a]	0.84[a]	0.49	0.25[a]	0.63[a]	0.53[a]
	Min	0.08[a]	0.03	0.00	0.10[a]	0.05	0.27[a]	0.25	0.47[b]	0.20	0.32[a]
Northwest	Max	0.09[b]	0.05	0.02	0.07	0.05[a]	0.34[b]	0.19	0.29[a]	0.33	0.29[a]
	Min	−0.03	−0.01	−0.02	−0.02	−0.01	0.37[a]	0.22	0.18[a]	0.23	0.25[b]
North Central	Max	0.08[b]	0.07[a]	0.05[a]	0.12[b]	0.07[a]	0.07	0.09	0.13	0.23	0.13
	Min	0.05[a]	0.01	−0.03	0.10[b]	0.02	0.30[a]	0.18	0.22[a]	0.29	0.25[a]
Northeast	Max	0.13[b]	0.08[b]	0.08[b]	0.16[b]	0.11[b]	0.19	0.01	0.11	0.29[a]	0.14[a]
	Min	0.06[a]	0.01	−0.03	0.06[a]	0.02	0.31[b]	0.26[a]	0.25[a]	0.27	0.27[a]
West Coast	Max	0.16[b]	0.10[b]	0.09[b]	0.14[b]	0.12[b]	0.3[b]	0.18[a]	0.20[a]	0.23[a]	0.23[b]
	Min	0.02	0.02	0.02[a]	0.04	0.02	0.29[a]	0.14[a]	0.17[a]	0.23	0.18[a]
East Coast	Max	0.10[b]	0.05[a]	0.04[a]	0.09[b]	0.06[b]	0.26[b]	0.18	0.10	0.16	0.17[a]
	Min	0.06[a]	0.04[a]	0.01	0.05[a]	0.04[a]	0.22	0.19[a]	0.18[a]	0.21[a]	0.18[a]
Interior Peninsula	Max	0.08[b]	0.04	0.03	0.07[a]	0.05[a]	0.25[a]	0.08	0.08	0.22	0.15[a]
	Min	0.06[a]	0.04[a]	0.02[a]	0.07[a]	0.04[a]	0.13	0.04	0.11[a]	0.18	0.10

[a]Significant at 5% level.
[b]Significant at 1% level.

winter and post-monsoon temperatures show significant warming trend (Table 1). The warming trend in all-India annual maximum temperature during the 1901–2003 is reflected almost all over the country, and also in all the seasons, though being relatively more extensive in the dry winter and post-monsoon seasons. On the contrary, the areal extent under significant warming trend in maximum temperatures is substantially reduced during the last three decades in all the seasons (Table 2).

[11] All-India mean annual minimum temperature does not show significant trend during the period 1901–2003; however, on the seasonal scale, winter and post-monsoon seasons show significant warming trend of 0.04°C and 0.07°C/10 yr. Interestingly, there appear to be some conspicuous decadal variations in the minimum temperature during the later half of the past century. Up to about 1955, the all-India mean annual minimum temperature did not show any systematic change, but after 1955, it decreased sharply up to 1970 and later it has been gradually increasing (Figure 2). This has resulted in a significant warming trend of 0.21°C/10yr over the last three decades, which is mainly due to significant warming over the northern regions (Table 1). The trends are positive in all the four seasons; however, they are significant only in winter and monsoon seasons. In terms of spatial extents of significant trends, the minimum temperature has shown relatively greater area under warming trends during 1901–2003, which period is also marked by some areas under cooling trends mainly in the monsoon season (Table 2). However, during the last three decades, the area under significant cooling trends has almost disappeared, and the monsoon season is marked by the greatest area under warming trend.

[12] The recent change in the diurnal asymmetry of trends is most conspicuous, and indeed in the opposite direction, in the northern parts of the country, particularly over the NW and NC regions (Table 1). In this context, it may be noted here that it was in this region that *Rupa Kumar et al.* [1994] reported diurnal asymmetry conspicuously different from other parts of the world. Now the diurnal asymmetry is more uniform over the country. On the whole, while the total area under significant warming trend is considerably reduced during the recent period for maximum temperature, it is maintained or even increased in the case of minimum temperature (Table 2). This can be considered as a characteristic recent change in the nature of temperature trends over the region, both in terms of seasonal and diurnal asymmetries.

4. Conclusions

[13] All-India mean annual temperature has increased by 0.05°C/10yr for the period 1901–2003. In the recent three decades (1971–2003), the all-India mean annual temperature has increased by 0.22°C/10yr, marking a substantial acceleration of the warming trend in the recent period. While the significant warming trend over the past century appears to be mostly due to the maximum temperature (0.07°C/10yr) when the entire period 1901–2003 is considered, notable turn-around in this diurnal asymmetry becomes evident during the last three decades. During the

Table 2. Area (% of The Total Area of the Country) Under Warming and Cooling Trends During the Two Periods 1901–2003 and 1971–2003

	Warming Trend Area (%)				Cooling Trend Area (%)			
	Max. Temp.		Min. Temp.		Max. Temp.		Min. Temp.	
Season	1901–2003	1971–2003	1901–2003	1971–2003	1901–2003	1971–2003	1901–2003	1971–2003
DJF	70	39	44	37	0	1	7	0
MAM	38	9	24	22	0	0	8	0
JJAS	43	20	16	48	2	0	17	1
ON	59	28	53	17	0	0	3	0
Annual	63	31	34	36	0	0	7	0

period 1971–2003, significant warming in both maximum (0.20°C/10yr) and minimum temperatures (0.21°C/10yr) contributed to the accelerated warming trend. This is largely due to the anomalous surge in warming over the last decade of the data period.

[14] In terms of spatial extent, the country is marked by widespread increasing trends in the maximum temperature in all the seasons for the whole period 1901–2003, with no region/season showing cooling trends. During the period 1971–2003, though the all-India mean annual maximum temperature still shows significant warming trend, the area under the significant warming trend has reduced notably from that during the whole period.

[15] Minimum temperatures during the monsoon season have shown significant increasing trends during the recent period over almost all the regions, which is quite contrary to the trends observed over the full data period 1901–2003. This has contributed to a major shift in the seasonal asymmetry of temperature trends over the region. It is believed that temperature anomalies associated with large-scale monsoon anomalies persist through the following dry season. Given the fact that the Indian summer monsoon has displayed conspicuous decadal variability [*Pant and Rupa Kumar*, 1997], it is reasonable to attribute some of the decadal changes in temperature trends to monsoon variability. However, the surge in warming trend during the last decade could be an integral part of the global warming signature, as the last decade has recorded some of the highest temperature anomalies in recorded history even on the global scale. Thus, while the recent changes in the trends noted here are possibly modulated by the associated decadal changes in the Indian summer monsoon activity, the results of the present study could be a pointer to the region gradually coming under the globally more extensive regime of increasing night-time temperatures already documented by several other studies.

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