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Surface air temperature variability over India during 1901–2007, and its association with ENSO

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ABSTRACT: Seasonal and annual trends in surface air temperature over India and 7 homogeneous regions (western Himalaya, northwest, north-central, northeast, east coast, west coast and interior peninsula) were assessed during 3 periods: 1901–2007, 1971–2007 and 1998–2007. Indian annual mean (average of maximum and minimum), maximum and minimum temperatures showed significant warming trends of 0.51, 0.72 and 0.27°C 100 yr^{-1}, respectively, during the period 1901–2007. However, accelerated warming was observed in the recent period 1971–2007, mainly due to intense warming in the recent decade 1998–2007. Temperatures (mean, maximum and minimum) increased by about 0.2°C per decade for the period 1971–2007, with a much steeper increase in minimum temperature than maximum temperature. In the most recent decade, maximum temperature was significantly higher compared to the long-term (1901–2007) mean, with a stagnated trend during this period, whereas minimum temperature showed an increasing trend, almost equal to that observed during 1971–2007. On a seasonal scale, pronounced warming trends in mean temperature were observed in winter and monsoon seasons, and a significant influence of El Niño Southern Oscillation events on temperature anomalies during certain seasons across India was observed. The composites of maximum and minimum temperatures of El Niño years showed positive anomalies during monsoon, post-monsoon and subsequent year winter and pre-monsoon seasons. However, statistically significant positive anomalies were observed only during monsoon and post-monsoon seasons over large areas of the country. The composite temperature anomalies of La Niña years were almost opposite to El Niño composites: the negative temperature anomalies associated with La Niña events persisted from the current monsoon season to the subsequent year pre-monsoon season.

KEY WORDS: India · Temperature trend · Decadal average temperature · Global warming · ENSO

1. INTRODUCTION

Atmospheric temperature is one of the most important characteristics of the climate system and is widely used as a measure of climate change on regional, hemispheric as well as global scales. Indeed, over the last few decades, global warming has come to be viewed as the main issue of climate change. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC 2007) reported that global mean surface air temperature has increased by 0.7°C in the past century. However, in the context of global warming, regional manifestations of temperature variation assume special importance as warming is not uniform across the globe.

Interest in studying temporal variation in temperature over India started relatively early, when the availability of sufficiently long-term instrumental records allowed Pramanik & Jagannathan (1954) to examine the trends of maximum and minimum temperatures of 30 Indian stations for the period 1880–1950. They concluded that there was no general tendency for a systematic increase or decrease in maximum and minimum temperatures. In one of the earliest studies in the context of contemporary global warming, Hingane et al. (1985), with temperature data from 73 stations, reported that the mean annual temperature of India increased by about 0.4°C during the 20th century. Kothawale (1992) reported that the mean annual maximum temperature increased by about 0.5°C yr^{-1} during the past century, while there was no

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systematic change in the minimum temperature. Srivastava et al. (1992) studied decadal trends in the climate over India and reported widespread cooling over northern India and warming over southern India. Rupa Kumar et al. (1994) pointed out that while the mean temperature trends over India were similar to global and hemispheric trends, the diurnal asymmetry of surface temperature trends observed over India is quite different from that noted in the other parts of the world (Karl et al. 1993). The increase in the mean temperature over India was almost solely due to the maximum temperatures (0.6°C 100 yr^{-1}), with the minimum temperature remaining practically trendless. Consequently, there was a general increase in the diurnal temperature range over India. Krishnan & Ramanathan (2002) have suggested that the Indian surface air temperature during the drier part of the year (January to May) has been subjected to a relative cooling by as much as 0.3°C during the last 3 decades (1968–1997), when the global effects of greenhouse gases and natural variability are filtered out from the temperature series. However, Kothawale & Rupa Kumar (2005) pointed out that this is a perceived cooling, and Indian annual maximum and minimum temperatures have significantly increased during the recent 3 decades (1971–2003).

Global to regional temperature variability is known to be influenced by the El Niño Southern Oscillation (ENSO) phenomenon (Kiladis & Diaz 1989). Halpert & Ropelewski (1992) examined the association between ENSO and global surface temperatures and reported that the ENSO influences the surface temperatures on regional and global spatial scales. A large part of the interannual variability of monsoon rainfall is also linked with the ENSO (Sikka 1980, Pant & Parthasarathy 1981, Krishna Kumar et al. 1995). However, the role of ENSO on the regional temperatures over India is neither well examined nor documented.

On the century scale, Indian average annual mean, maximum and minimum surface air temperatures have showed significant warming, and determining the decadal- to multidecadal-scale temperature variability is also equally important to understanding the epochal behavior, if any, within the time series. In view of this, in the present study, monthly temperature records updated until the recent period were used to examine the variability of temperature on decadal to longer time scales and were also compared with global temperature time series. The influence of ENSO on Indian surface air temperatures was also examined.

2. DATA AND ANALYSIS

The monthly maximum and minimum temperature data from 121 stations well distributed over the country during the period 1901–2007 were used in the present study. The data for the period 1901–1990 were sourced from monthly weather reports from the India Meteorological Department (IMD) in Pune, and the monthly data for the period 1991–2007 were estimated from daily data reported in the Indian Daily Weather Reports of the IMD. Adequate care has been taken in ensuring the homogeneity of the data. The outliers in the data were identified as such if the station's monthly temperature values were greater/less than the long-term mean by ±3 times the standard deviation of the corresponding month. The outliers identified in this manner were considered as missing and these accounted for <5% of the total number of data points. The missing values were then estimated using data from neighbouring stations by a regression technique (Rupa Kumar et al. 1994).

In order to project a more realistic temperature climatology onto the limited number of stations data used in the present study, climatological normals of monthly mean maximum and minimum temperatures for the period 1951–1980 for 388 well-spread stations were taken from IMD (1999). To prepare means of temperatures for India and 7 homogeneous regions within India, that—in spatial terms—are highly representative, the following procedure was adopted. Temperature data from 121 stations were converted to monthly anomaly time series for the period 1901–2007, with reference to the respective station normal values, and then were objectively interpolated onto a 0.5° × 0.5° grid, with a 3° search radius, using an inverse squared distance weighted average algorithm (Kothawale & Rupa Kumar 2005). The climatological normals (1951–1980) of temperature at 388 stations were then interpolated onto the same grid, resulting in a high-resolution grid point temperature climatology for the country. The gridded monthly anomaly values were then added to the gridded climatology based on 388 stations, producing a long-term gridded data set of actual temperatures for India for the period 1901–2007. The gridded mean temperature data sets were prepared by computing the averages of grid maximum and minimum temperatures. Regional monthly temperature series were computed by simple averaging of the constituent grid point data of the respective regions. In addition, ERSST v.3.4 (www.ncdc.noaa.gov/oa/climate/research/sst/sst.php) sea surface temperature (SST) data during the period 1901–2007 were also used.

To identify regional patterns of temperature variations within the country, annual and seasonal—winter (previous year December to February [DJF]), premonsoon (March to May [MAM]), monsoon (June to September [JJAS]) and post-monsoon (October to November [ON])—temperature series for the period 1901–2007 were constructed for India and 7 homogeneous regions within India: western Himalaya (WH), northwest (NW), north-central (NC), northeast (NE), east coast (EC), west coast (WC) and interior peninsula (IP). These regions (Fig. 1) were defined based on geographical, topographical and climatological features (Kothawale & Rupa Kumar 2005).

The regional annual and seasonal temperature series were examined for long-term variation in different sub-periods 1901–2007, 1971–2007 and 1998–2007. Trends were quantified by the slope of a simple linear regression fitted to each of the series against time. The statistical significance of a trend was assessed by means of the *F*-ratio (ANOVA), after taking into account any autocorrelation present in the series (Wigley & Jones 1981). Significance of the decadal as well as sub-period averages of maximum, minimum and mean temperatures from their long-term averages were examined using a Student's *t*-test.

3. RESULTS

3.1. Temperature trends

Annual and seasonal mean, maximum and minimum temperature series for India as well as for 7 different homogeneous regions of India were examined for long-term trends over the entire data period 1901–2007 and also separately for the periods 1971–2007 and 1998–2007. Trends are expressed per 100 yr for the longer 107 yr period (1901–2007) and per 10 yr for the recent 37 yr period (1971–2007). The secular variation in the temperature trends over smaller segments have also been examined by computing 31 yr sliding trends in annual as well as seasonal temperature series.

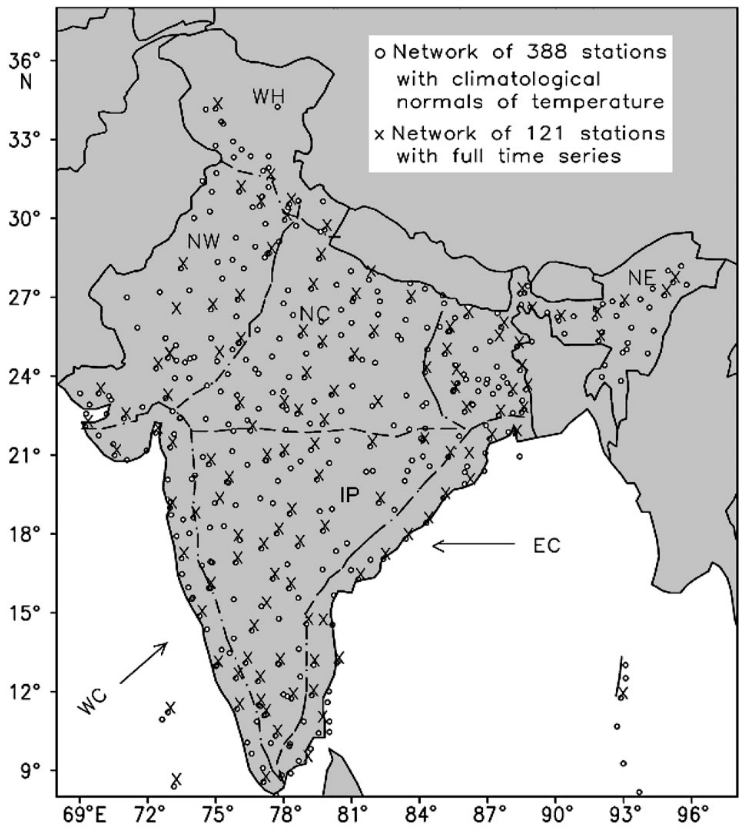

Fig. 1. Network of 121 and 388 temperature stations and homogeneous regions used in the present study. WH: western Himalaya; NW: northwest; NE: northeast; NC: north-central; EC: east coast; WC: west coast; IP: interior peninsula

3.1.1. Mean temperature

Indian mean annual temperature showed a significant warming trend of 0.51°C 100 yr^{-1} for the period 1901–2007; the temperature increased gradually and continuously over the entire period (Fig. 2a). This warming was mainly due to the winter and post-monsoon seasons (Table 1), whose temperatures significantly increased by 0.80 and 0.82°C 100 yr^{-1}, respectively ($p < 0.01$). Pre-monsoon and monsoon temperatures also indicated a significant warming trend, but they were relatively weaker ($p < 0.05$). In terms of consistency, the 31 yr sliding trends in Indian mean annual temperature indicate that the trends were positive from the beginning of the data period up to 1955 (approximately the middle of the data period), negative during the period 1955–1965 and continuously positive from 1965 to the present (Fig. 3). Recent 31 yr periods showed a significant warming trend.

When considering the entire data period, the significant warming trend in mean annual temperature is seen to be mostly due to maximum temperature, whereas the contribution of minimum temperature is much less (Table 1). However, during the recent 3 decades (1971–2007), annual mean temperature increased by 0.20°C 10 yr^{-1}, due to significant increases in both maximum and minimum temperatures. In fact, the increase in minimum temperature was more rapid than in maximum temperature, especially during winter, pre-monsoon and monsoon seasons. It may be noted that during the entire period 1901–2007, winter and post-monsoon temperatures showed relatively higher and more significant warming trends, but during the recent period 1971–2007, the post-monsoon temperature did not show any significant warming trend (only winter and monsoon seasons). This can have significant implications for yields of cereal crops, particularly rice (Peng et al. 2004 reported that rice yields decline with higher night temperatures).

Table 1 presents the linear trends in annual and seasonal temperatures of India and the 7 homo-

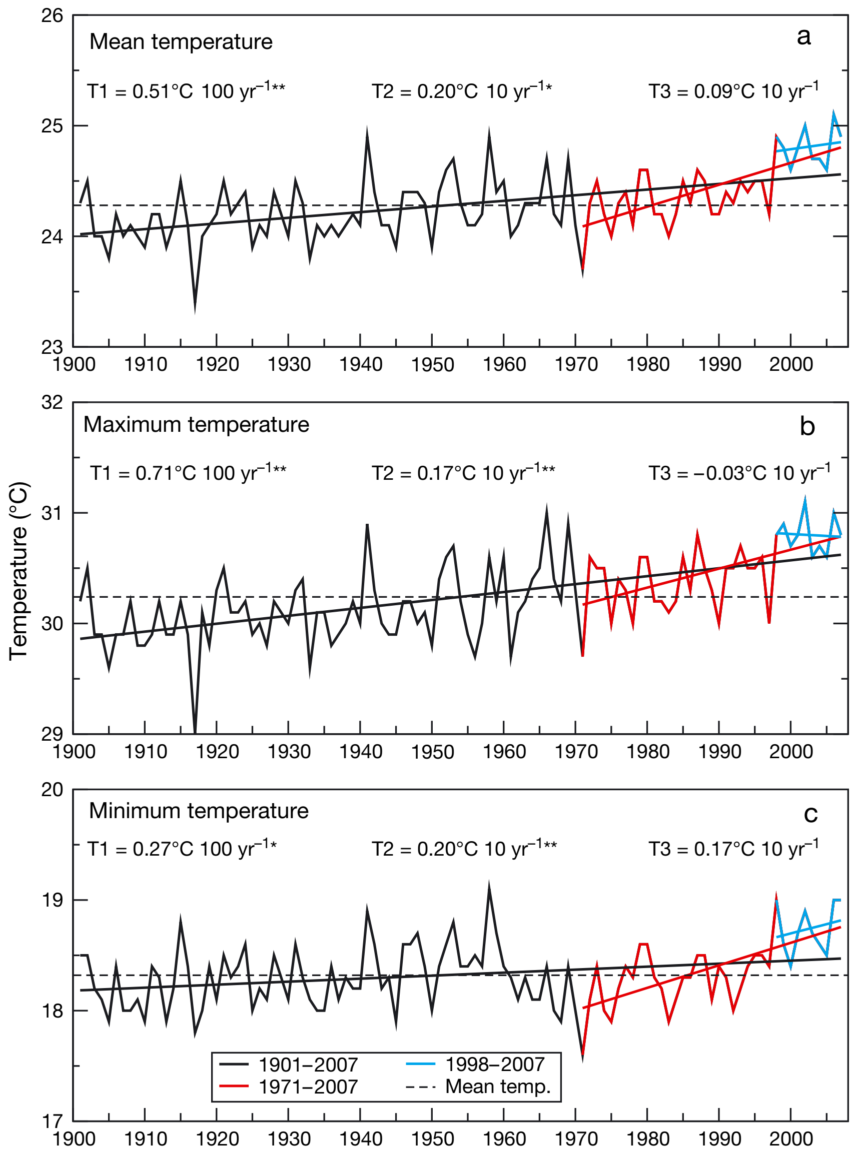

Fig. 2. Indian annual temperature variations during trend periods 1901–2007 (T1), 1971–2007 (T2) and 1998–2007 (T3). *$p < 0.05$; **$p < 0.01$

geneous regions for the periods 1901–2007 and 1971–2007. Of the 7 regions, 6 showed a significant warming trend in mean annual temperature for the period 1901–2007. On the seasonal scale, winter, pre-monsoon, monsoon and post-monsoon temperatures showed a significant warming trend over 6, 4, 4 and 6 regions, respectively. However, in the recent period 1971–2007, the number of regions showing significant warming trends in winter, pre-monsoon, monsoon and post-monsoon seasons were 7, 3, 5 and 2, respectively. On the whole, winter and summer monsoon temperatures showed a significant increasing trend over almost the entire country, while post-monsoon temperatures significantly increased over relatively smaller number of regions.

3.1.2. Maximum temperature

Mean temperature was calculated as the average of maximum and minimum temperatures. Hence we examined the spatial and temporal variability of maximum and minimum temperatures separately to determine which contributed more to Indian warming on different time scales.

Indian mean annual maximum temperature showed significant warming trends of 0.71°C 100 yr^{-1} and 0.17°C 10 yr^{-1} during the periods 1901–2007 and 1971–2007, respectively (Fig. 2b). However, in the recent decade 1998–2007, maximum temperature showed a slight negative trend of −0.03°C 10 yr^{-1}. The rise in temperature was quite gradual and continuous during the period 1901–2007, with no prolonged warm or cold epochs (Fig. 3). All seasons contributed to the warming trend in mean annual maximum temperature for the period 1901–2007; however, during the recent period, warming was mainly due to significant increases in temperature during the winter and post-monsoon seasons (Table 1). The 31 yr sliding trends in annual maximum temperature were positive in almost all the 31 yr periods, except during 1955–1970, where trends were slightly negative (Fig. 3).

The warming trend in Indian mean annual maximum temperature is reflected in almost all the homogeneous regions for the period 1901–2007 (Table 1). Four regions (NC, NE, WC and EC) showed a significant warming trend during all 4 seasons (Table 1), whereas the remaining 3 regions (WH, NW and IP) showed warming trends in winter and post-monsoon seasons only. For the period 1971–2007, only WH showed a warming trend in all seasons, while the remaining 6 regions showed significant warming in winter, and 1 or 2 regions showed significant warming in the pre- and post-monsoon seasons. It is important to note that only NE showed a cooling tendency in the pre-monsoon season. Thus the spatial extent of the significant warming trend is considerably reduced. These features are reflected in the spatial patterns of seasonal trends for the 2 periods 1901–2007 and 1971–2007.

Table 1. Linear trend in annual and seasonal temperature (°C) for India and 7 homogeneous regions within India: western Himalaya (WH), northwest (NW), north-central (NC), northeast (NE), west coast (WC), east coast (EC) and interior peninsula (IP). DJF: previous year Dec–Feb; MAM: pre-monsoon Mar–May; JJAS: monsoon Jun–Sep; ON: post-monsoon Oct–Nov. *p < 0.05; **p < 0.01

Region	Temperature	1901–2007 (°C 100 yr^{-1})					1971–2007 (°C 10 yr^{-1})				
		DJF	MAM	JJAS	ON	Annual	DJF	MAM	JJAS	ON	Annual
India	Maximum	1.1**	0.61**	0.43**	0.96**	0.72**	0.27**	0.10	0.10	0.21**	0.17**
	Minimum	0.46*	0.23	−0.06	0.64**	0.27*	0.30**	0.18*	0.18**	0.18	0.20**
	Mean	0.8**	0.42*	0.20*	0.82**	0.51**	0.30**	0.14	0.14**	0.20	0.20**
WH	Maximum	1.8**	1.3*	0.38	0.85	1.0*	0.82*	0.68*	0.22*	0.49*	0.53*
	Minimum	1.16**	0.45	0.10	1.10**	0.61*	0.47**	0.30*	0.40**	0.26	0.37**
	Mean	1.5**	0.91*	0.24	1.00*	0.86**	0.68**	0.49*	0.35*	0.39*	0.46**
NW	Maximum	0.88**	0.50	0.25	0.67	0.53**	0.28*	0.18	0.19	0.23	0.22*
	Minimum	−0.18	0.00	−0.26*	0.15	−0.11	0.40	0.25**	0.11*	0.18	0.24**
	Mean	0.34	0.28	−0.02	0.40	0.21	0.34**	0.22	0.15	0.21	0.22**
NC	Maximum	0.82**	0.60*	0.45*	1.1**	0.67**	0.15	0.03	0.08	0.17	0.10
	Minimum	0.60**	0.16	−0.23	1.06**	0.29	0.36**	0.19	0.20**	0.19	0.22*
	Mean	0.71**	0.36	0.09	1.10**	0.50**	0.25*	0.11	0.13*	0.20	0.17**
NE	Maximum	1.2**	0.66*	0.72**	1.4**	0.95**	0.17	−0.02	0.09	0.17*	0.09*
	Minimum	0.64	0.15	−0.23	0.60	0.22	0.34**	0.23*	0.22**	0.19	0.24**
	Mean	0.95**	0.39	0.25*	1.02**	0.60**	0.27**	0.11	0.17**	0.19	0.18**
WC	Maximum	1.6**	0.99**	0.90**	1.3**	1.1**	0.29**	0.16*	0.13	0.18*	0.19**
	Minimum	0.21	0.30*	0.28**	0.42*	0.27*	0.25*	0.15**	0.16**	0.20	0.18*
	Mean	0.91**	0.63**	0.59**	0.84**	0.74**	0.27**	0.16*	0.15**	0.19*	0.19**
EC	Maximum	1.0**	0.46*	0.36*	0.81**	0.63**	0.25**	0.10	0.06	0.09	0.11**
	Minimum	0.54*	0.40**	0.11	0.43*	0.35*	0.16	0.15**	0.14*	0.13	0.13*
	Mean	0.79**	0.41**	0.24*	0.60**	0.49**	0.20*	0.13*	0.10	0.11	0.12*
IP	Maximum	0.93**	0.36	0.28	0.68*	0.54**	0.27**	0.03	0.05	0.18	0.12*
	Minimum	0.53*	0.39*	0.24*	0.60*	0.44**	0.09	0.05	0.11*	0.11	0.09
	Mean	0.73**	0.34*	0.26*	0.63**	0.48**	0.18*	0.04	0.09	0.13	0.10*

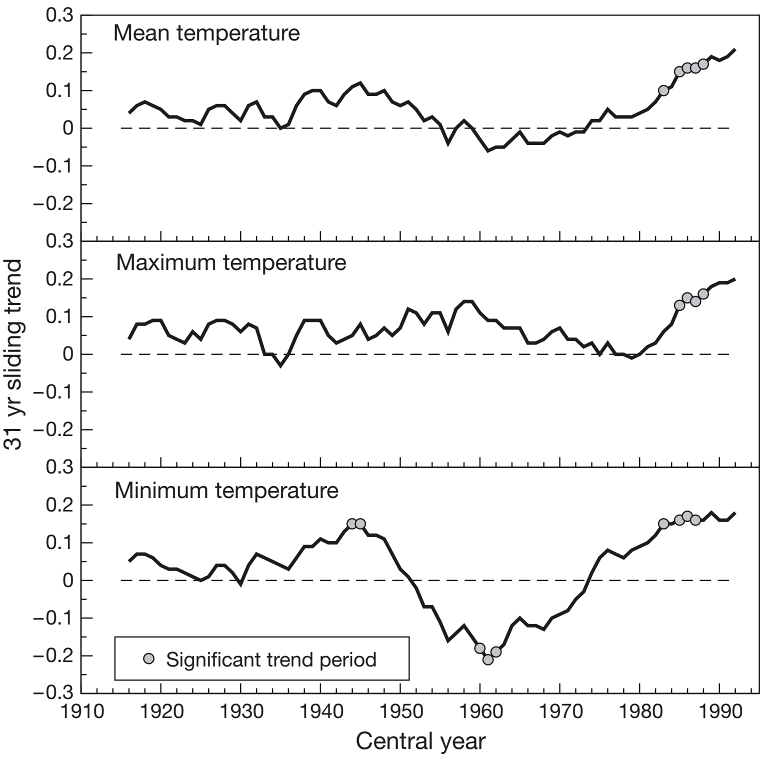

Fig. 3. Sliding trend (31 yr) in Indian annual temperatures (°C)

3.1.3. Minimum temperature

Indian mean annual minimum temperature significantly increased by 0.27°C 100 yr^{-1} during the period 1901–2007 (Fig. 2c), the warming mainly due to winter and post-monsoon temperatures. However, the results presented here are somewhat different from those reported in Kothawale & Rupa Kumar (2005), where Indian annual minimum temperature showed a very weak increasing trend that was not statistically significant. However, their analysis is based on data during the period 1901–2003. Warming during the 2004–2007 may have played a vital role in making the trend statistically significant in our analysis.

There are some conspicuous changes in minimum temperature for different sub-periods. During the period 1901–1955, Indian mean annual minimum temperature showed a warming tendency, but after 1955 it decreased sharply until 1970 and then gradually increased. The 31 yr sliding trends also clearly bring out these features (Fig. 3). In the recent 3 and a half decades, Indian mean annual minimum temperature showed a significant warming trend of 0.20°C 10 yr^{-1}. Unlike maximum temperature, the trend in minimum temperature during the most recent decade was maintained at the rate noted for the recent 3 and half decades. On a seasonal scale, all seasons showed a significant warming trend except the post-monsoon season, where the trend was positive but not significant (Table 1).

3.2. Spatial patterns of temperature trends

In the previous section we discussed the trends in spatially aggregated means pertaining to India and the 7 homogeneous regions during 3 different periods. However, these results do not indicate which regions in the country show significant positive/negative trends in different seasons and in different periods of interest. In view of this, we present here a detailed analysis of spatial trends of mean, maximum and minimum temperatures for all 4 seasons (DJF, MAM, JJAS and ON) and annually during 1901–2007, 1901–1970 and 1971–2007. Before describing the major findings of this analysis, we wish to state here that the temperature trends in India are highly influenced by the low-frequency variability of rainfall during the monsoon season over a major part of the country and during the post-monsoon season in the extreme southeastern peninsula. Also, several other regional factors, such as topography, land-use and land-cover changes, and anthropogenic aspects, such as the presence of aerosols and black carbon, determine the trends on smaller spatial scales compared to the Indian aggregated trends. While we present several maps depicting these spatial trends (see Figs. A1–A3 in Appendix 1), only salient features are discussed below.

Spatial patterns of linear trends in mean temperature based on the period 1901–2007 were positive over large areas of the country during all seasons; however, winter and post-monsoon temperature trends were highly statistically significant over large areas of the country as compared to rest of the seasons (Fig. A1). Negative trends in mean and minimum temperature were observed over part of northern India prior to the 1970s; however, significant warming trends were observed in the monsoon season during the recent period 1971–2007. Though it is beyond the scope of the present study, it is worth mentioning here that Indian mean monsoon rainfall has remained in a below-normal epoch in the last 4 to 5 decades, and this could be one of the factors contributing to the significant warming trends noted in the monsoon season, besides the globally increasing greenhouse gas emissions. The significant warming observed over a large part of the country during 1901–2007 is mainly due to the warming in recent decades. Spatial patterns of maximum temperature trends were similar to mean temperature trends (Fig. A2); however, spatial patterns of minimum temperature trends were slightly different from maximum temperature trends. The negative trends in minimum temperature were seen over large areas of northern India in almost all seasons during the period 1901–2007, whereas negative trends in maximum temperature occurred in only a few areas throughout the country. The most conspicuous change noted in these spatial patterns is the reversal of trends from negative to strongly positive over most of northern India in the recent period of 1971–2007. Similarly, Srivastava et al. (1992), using data for the period 1901–1986, reported that annual mean minimum temperatures showed a cooling trend over the northern parts (north of 24° N) of India.

The progressively increasing warming that is noted from 1901–2007 in different sub-periods is further demonstrated by the difference in mean temperatures between the period pairs of: (1) 1971–2007 and 1901–1970, (2) 1998–2007 and 1971–1997 and (3) 1998–2007 and 1901–1997. The differences in mean temperature between these pairs were tested using the Student's *t*-test. From Fig. 4 it can be seen that cooling seen in a major part of the Indo-Gangetic plain areas in northern India has been replaced by warming, although a few small pockets of cooling remain in the eastern parts of northern India. The cooling observed over the Indo-Gangetic region could be due to the presence of aerosols and related solar dimming (Sarkar et al. 2006, Padma Kumari et al. 2007). The significant warming observed in the recent decades is in line with some of the model-projected temperature changes over India (Krishna Kumar et al. 2005, Turner et al. 2007).

4. INDIAN AND GLOBAL TEMPERATURE TRENDS

Fig. 5 shows Indian and global mean annual and seasonal temperature variability during the period 1901–2007. The global temperature anomalies were obtained from the Climate Research Unit (www.cru.uea.ac.uk/cru/data/temperature/). The anomalies have been computed with respect to 1961–1990 climatology.

The global mean annual and seasonal (DJF, MAM, JJAS and ON) temperatures significantly increased by 0.82, 0.89, 0.94, 0.72 and 0.76°C 100 yr^{-1}, respectively, during the period 1901–2007. Indian mean temperature also showed a significant warming trend of 0.51, 0.80, 0.42, 0.20 and 0.82°C 100 yr^{-1}, respectively, during annual, DJF, MAM, JJAS and ON seasons. However, there are marked differences in the magnitude of seasonal trends of Indian and global temperatures (Fig. 5). The magnitude of the increasing trend of the winter and post-monsoon seasons are almost same for

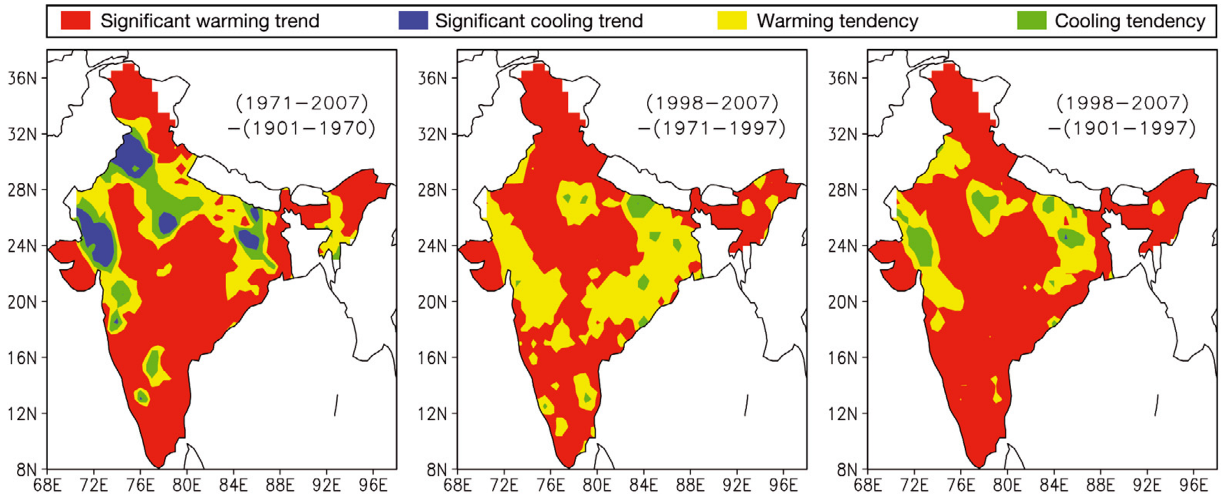

Fig. 4. Significant change in annual mean temperature for different periods

these 2 areas, while pre-monsoon and monsoon temperature trends for India are almost less than half of the global trends. Indian temperature variability during the monsoon season is mainly constrained by rainfall activity, negative anomalies during a strong monsoon and vice versa, while for other parts of globe, rainfall activity is not as seasonal or intense as it is over India (the rainy season consists of only 4 mo across most of India). This results in a weak trend in monsoon temperature over India as compared to globally. The pre-monsoon temperatures over India are also affected by rainfall during this season; however, pre-monsoon rainfall is much less than monsoon season rainfall.

5. IMPACT OF ENSO ON INDIAN TEMPERATURE

The ENSO phenomenon is one of the most important sources of interannual climate variation over various parts of the world (Kiladis & Diaz 1989, Ropelewski & Halpert 1987). The Southern Oscillation (SO) is a global-scale seesaw of surface pressure with centers of action around Indonesia (Indian Ocean region) and the southeast Pacific, whereas El Niño is associated with significant warm temperatures over the eastern equatorial Pacific. These 2 phenomena occur simultaneously, the SO being the atmospheric phenomenon and the El Niño being an oceanic phenomenon. There is a strong association between El Niño events over the eastern equatorial Pacific and deficient monsoon rainfall of India; nearly 60 % of major droughts over India have occurred in association with El Niño events. The occurrence of unusually cold anomalies in SST in the ENSO region is generally referred to as La Niña and is generally associated with above-normal or excess summer monsoon rainfall over the Indian region.

Very few studies have examined the role of ENSO in influencing regional temperatures, particularly over India. Therefore, we examined the link between ENSO and Indian temperatures on interannual and low-frequency multidecadal time scales. The latter will also be examined with respect to Indian Ocean SST. First, to examine the interannual links between ENSO and Indian temperatures, we correlated Indian annual mean temperature time series with annual global SST. Both the Indian temperature and SST time series at every grid point were detrended before the correlations were computed. Fig. 6 shows the pattern of correlation between Indian mean annual temperature and global SST during 1901–2007. It is clear that on interannual time scales, Indian mean temperatures are strongly correlated with SST in the eastern Pacific and the equatorial Indian Ocean. The pattern of significant correlations in the Pacific resembles the well-known pattern of SST associated with ENSO. It is also interesting to note that the correlations are equally strong and significant in the equatorial Indian Ocean. On the basis of the spatial pattern of correlations, regions which are highly correlated with the Indian temperatures were identified and their monthly SST series were constructed by taking a simple arithmetic average of grid data of the respective regions. The identified regions are 180° to 90° W and 10° S to 10° N (ENSO region) and 40° to 100° E and 0° to 26° N (North Indian Ocean). Indices of raw SST (not detrended) representing these 2 oceanic regions were later used to examine their possible influence on the low-frequency behaviour of Indian temperature.

Once we recognized that Indian mean annual temperatures were strongly correlated with ENSO, we further examined this association by making composite temperature anomalies of maximum and minimum

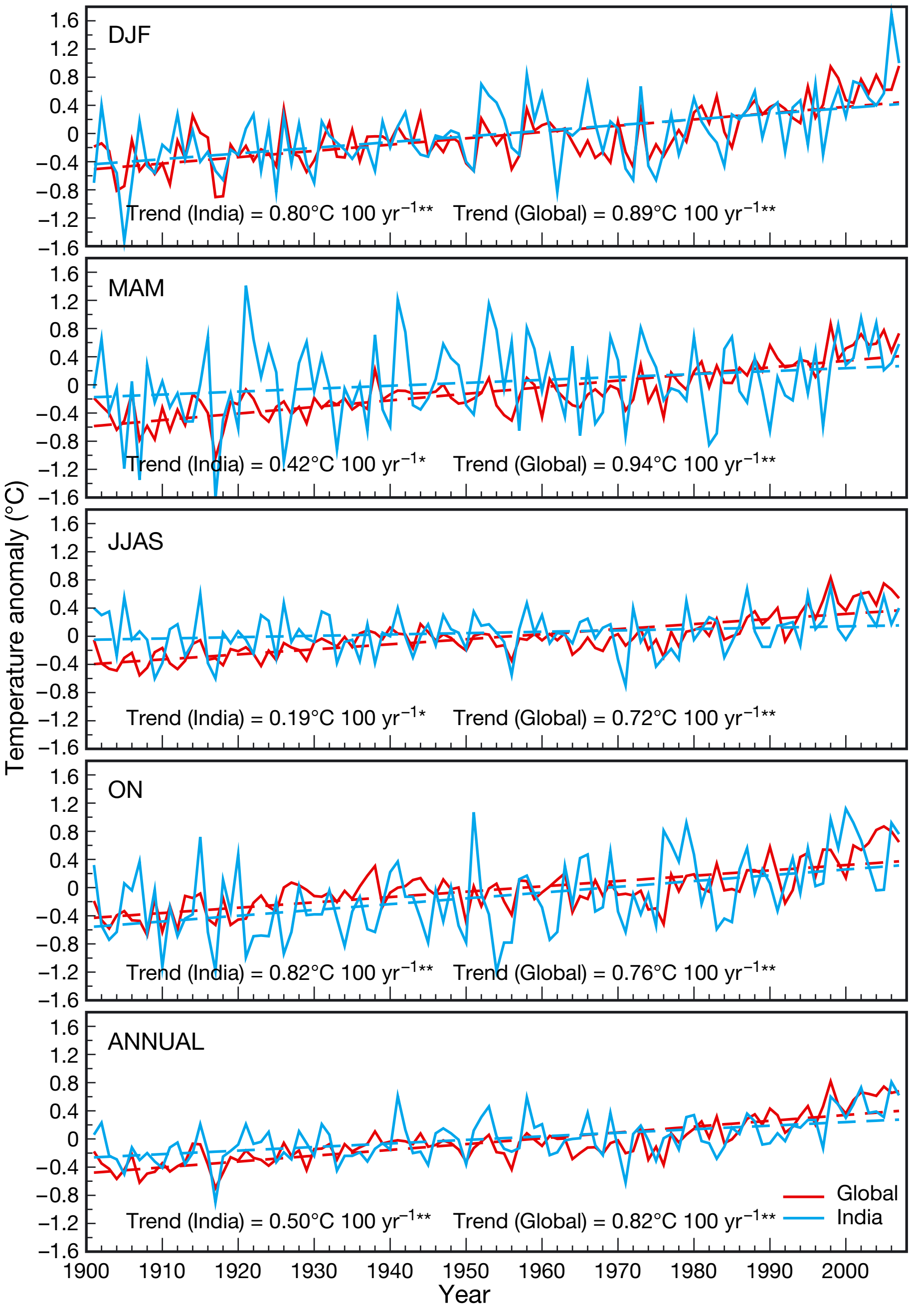

Fig. 5. Global (red) and Indian (blue) annual and seasonal mean temperature variations during the period 1901–2007. *$p < 0.05$; **$p < 0.01$. DJF: previous year Dec–Feb; MAM: pre-monsoon Mar–May; JJAS: monsoon Jun–Sep; ON: post-monsoon Oct–Nov

temperatures over India with regard to El Niño/La Niña events. These composites were made from the detrended gridded (0.5° × 0.5°) temperature data sets for the period 1901–2007. Composites of standardized seasonal (JJAS, ON, DJF, next year MAM and JJAS) temperature anomalies over India were computed by averaging the anomalies for 27 El Niño years (1905, 1911, 1912, 1914, 1918, 1919, 1923, 1925, 1930, 1932, 1940, 1941, 1946, 1951, 1953, 1957, 1965, 1968, 1972, 1977, 1982, 1987, 1991, 1992, 1997, 2002 and 2006) and 21 La Niña years (1904, 1909, 1910, 1915, 1917, 1924, 1928, 1938, 1950, 1955, 1956, 1964, 1970, 1971, 1973, 1975, 1988, 1998, 1999, 2000 and 2007). In order to capture the ENSO cycle, annual means of standardised anomalies were computed for the period June to May. A few El Niño/La Niña years occurred in consecutive years; in such cases, we considered the next El Niño/La Niña year for the composites (e.g. 1918 and 1919 are

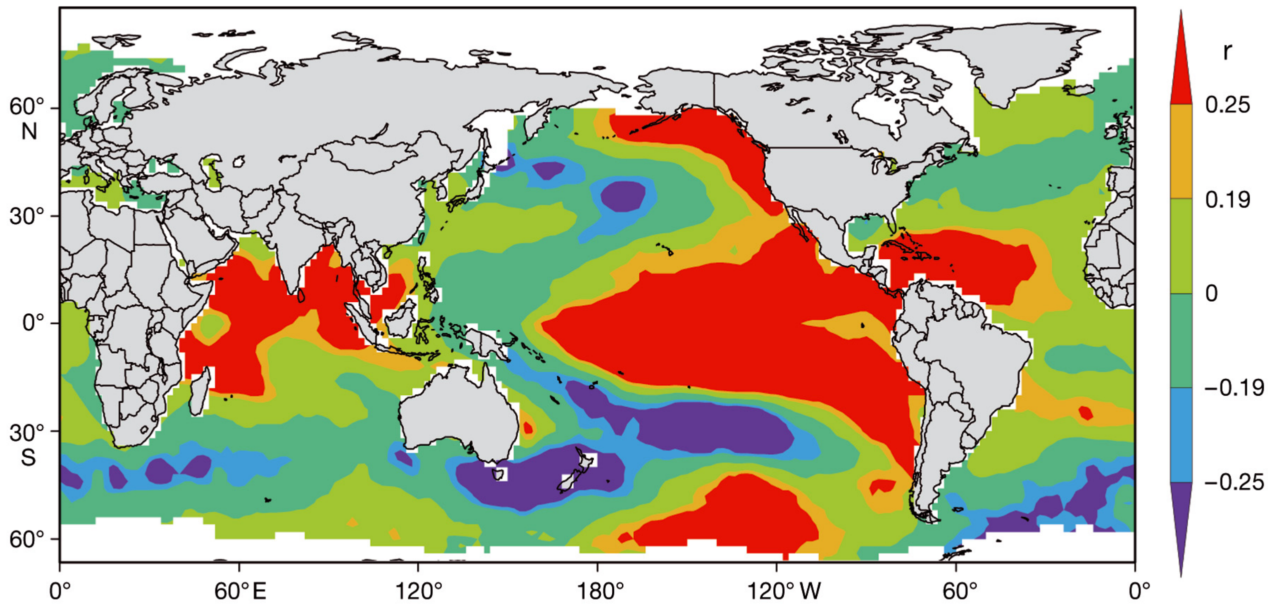

Fig. 6. Correlation between detrended mean annual Indian and global sea surface temperatures (°C), 1901–2007

2 El Niño years, we considered 1919 only). These years are mainly taken from Halpert & Ropelewski (1992) and updated to cover recent events. Halpert & Ropelewski (1992) used the criteria for selecting low ENSO phases (El Niño)/high ENSO phases (La Niña) as years during which the Tahiti-Darwin SO index remained in the lower/upper 25% of the distribution for 5 mo or longer. Using the grid-point temperature composites, the spatial patterns were plotted for El Niño and La Niña events. These composites were tested for statistical significance using the Student's *t*-test. Here, significant anomalies are identified by comparing the composite temperatures during El Niño/La Niña years with those during the normal years.

5.1. Maximum temperature anomaly composites of El Niño/La Niña years

The spatial patterns of the composites of standardised anomalies of seasonal maximum temperature for El Niño/La Niña events are shown in Fig. A4a,b. The composites of maximum temperature anomalies were positive during the monsoon, post-monsoon and winter seasons, as well as the next year pre-monsoon and monsoon seasons. However, strong positive anomalies were observed during the monsoon and post-monsoon seasons over large areas of the country. Specifically, maximum temperatures were substantially higher during the monsoon season due to deficient rainfall over a major part of India in association with El Niño events. We found the composites of maximum temperatures for drought years were also significantly higher compared to normal years during monsoon and post-monsoon seasons (data not shown), indicating a strong association between monsoon droughts and El Niño events.

La Niña events, on the other hand, were associated with more rainfall during the monsoon season and cooling (Fig. A4b). In the subsequent seasons, the influence of La Niña events was gradually reduced from the post-monsoon to the next year pre-monsoon seasons, and the anomalies become positive during the next year monsoon season. This reversal of temperature anomalies from the current year to the next year monsoon in La Niña composites indicates the biennial nature of monsoon rainfall (Meehl 1994), though the reversal of anomalies is not very conspicuous in the case of El Niño events (Fig. A4a). The spatial patterns of composite temperature anomalies during La Niña events are almost opposite to those observed during El Niño events (Fig. A4a). This corroborates the findings of Kothawale & Rupa Kumar (2002), who have shown a strong negative simultaneous correlation between Indian monsoon mean surface temperature and monsoon rainfall.

5.2. Minimum temperature anomaly composites of El Niño/La Niña years

The composite minimum temperature anomalies corresponding to El Niño events were positive during all seasons. The anomalies were weak during the monsoon season and more pronounced during post-monsoon and next year winter seasons (Fig. A5a). It is intriguing that minimum temperatures during the monsoon season were not influenced much by El Niño events, as was noticed in the case of maximum temperatures. This is partly due to the complex interaction between radiation and clouds. Though the relatively lower rainfall that occurs in the El Niño years should be associated with a relatively lower amount of cloud in the case of monsoon seasons, the fraction of cloud may not be entirely nil and hence the impact of El Niño events on monsoon season minimum temperature is not very strong.

The minimum temperatures during monsoon, post-monsoon and next year winter and pre-monsoon seasons were affected by La Niña events, and the anomalies were negative. Winter temperature anomalies were more pronounced compared to the rest of the seasons. It is hard to find the signature of biennial cycle in the minimum temperature composites.

5.3. Low-frequency variability of Indian temperatures and the role of SST

As described earlier, the annual Indian mean temperature and SST time series representing ENSO and the North Indian Ocean were prepared for the period 1901–2007. In order to capture the ENSO cycle, the annual temperature series of these regions were constructed by averaging the data during the ENSO year, June to the following May. These 3 time series are shown in Fig. 7 along with their respective filtered (5th degree polynomial) time series, capturing the low-frequency variability. From Fig. 7, it can be seen that the North Indian Ocean SST is monotonously increasing during the entire period without much decadal-scale variability. The low-frequency variability of SST in the ENSO region and Indian temperatures showed an in-phase behaviour throughout almost the entire period, except in the very recent period where they were opposite. The lack of coherency between ENSO SST and Indian temperatures are in general agreement with the findings of Krishna Kumar et al. (1999), who have shown that the relation between the Indian monsoon and ENSO weakened in recent decades.

Though Indian temperature and ENSO SST were strongly related on the low-frequency time scales compared to the Indian Ocean SST (where a monotonous increasing trend dominated), when we examined the 31 yr sliding correlations between the detrended time series of Indian temperatures and SST indices of ENSO and the North Indian Ocean, the relationship between ENSO and Indian temperatures was statistically significant up to 1980s, but weakened thereafter. On the other hand, the relationship between North Indian Ocean and Indian temperatures is strong throughout the data period, indicating a strong interannual link between Indian temperatures and Indian Ocean SST (data not shown).

6. CONCLUSIONS

In view of the importance of understanding the regional manifestation of global warming, we have presented a very comprehensive analysis of trends in mean, maximum and minimum temperatures over India using temperature data during 1901–2007. On larger spatially aggregated scales, the trends are quite consistent and are very much in agreement with global and hemispheric trends. However, on smaller regional scales and for different sub-periods, trends were not always consistent with those corresponding to Indian aggregated temperatures. This, we believe, is due to different factors that might be influencing the trends on seasonal and smaller regional scales. Furthermore, the trends are influenced by the variability of rainfall in the monsoon and post-monsoon seasons and, in the recent period, the relative influence of greenhouse gases and aerosols (and the relative composition of absorbing and radiating aerosols) may also play a role in some parts of the country. The impact of ENSO on the Indian temperatures is not well documented and hence we made an attempt here to provide some insights into this aspect as well. The following are some of the major findings of the present study:

(1) Indian mean, maximum and minimum annual temperatures have significantly increased by 0.51, 0.71 and 0.27°C 100 yr^{-1}, respectively, during 1901–2007. However, an accelerated warming was observed during 1971–2007, mainly due to the last decade 1998–2007.

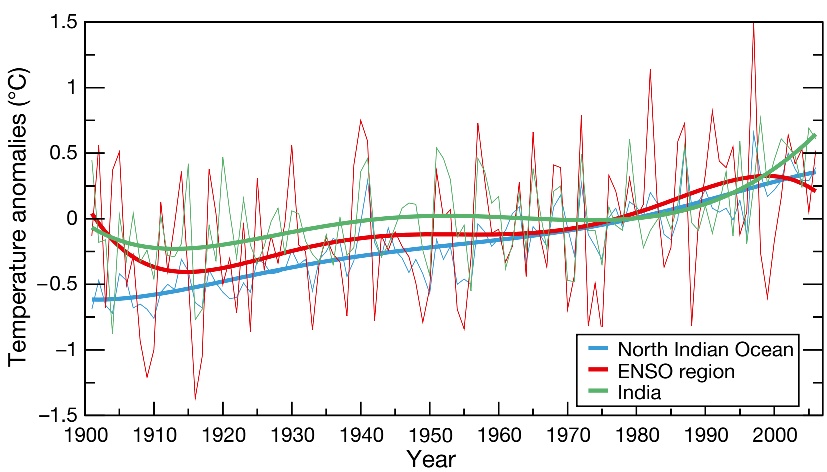

Fig. 7. Annual (current year June to next year May) temperature (°C) variability over different regions, 1901–2007. Thin lines: actual temperature series; thick lines: data smoothed by a 5 degree polynomial

(2) In the most recent decade, maximum temperature was significantly higher compared to the long-term (1901–2007) mean, with a stagnated trend during this period. In contrast, minimum temperature showed an increasing trend during the last 10 yr, almost equal to the magnitude of the trend observed during the 1971–2007 period.

(3) On the seasonal scale, maximum temperature has significantly increased in all seasons during the period 1901–2007; however, for the recent period only, winter and post-monsoon temperatures showed significant warming trends and the other seasons showed a warming tendency (trend not significant). In contrast, minimum temperature showed a significant warming trend in most seasons during 1971–2007.

(4) Average mean, maximum and minimum annual temperatures during the period 1998–2007 have significantly increased throughout India as compared to the long-term (1901–1997) mean.

(5) The global mean annual and seasonal (DJF, MAM, JJAS and ON) temperatures have significantly increased by 0.82, 0.89, 0.94, 0.72 and 0.76°C 100 yr^{-1}, respectively, during the period 1901–2007. Indian mean annual and seasonal temperatures also showed a significant warming trend in all seasons. The magnitude of the warming trend of winter and post-monsoon seasons was almost the same for these 2 areas, while pre-monsoon and monsoon temperature trends for India were half that of the global trend.

(6) It is evident that ENSO is impacting the Indian temperatures significantly. The composite maximum temperature anomalies of El Niño years were statistically significant and positive during monsoon and post-monsoon seasons over large areas of the country. In contrast, the composite anomalies of La Niña years were almost opposite of El Niño years. Though we see a biennial cycle in the maximum temperature composites associated with El Niño/La Niña events, it is hard to find the same in the minimum temperature composites.

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Appendix 1. Spatial patterns of linear trends in temperature for the periods 1901–2007, 1901–1970 and 1971–2007. Trends for the periods 1901–2007 and 1901–1970 are per 100 yr, and those for 1971–2007 are per 10 yr

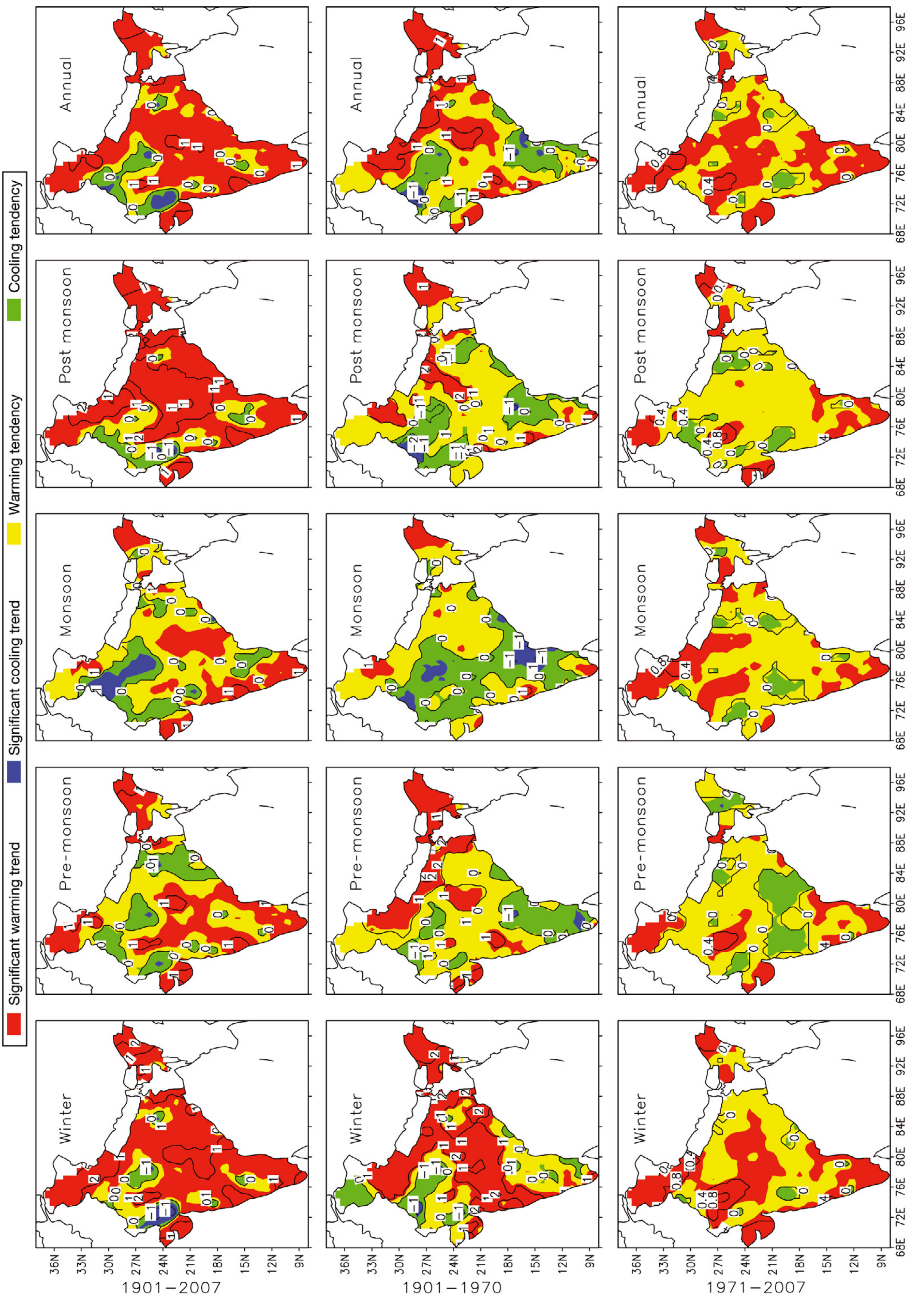

Fig. A1. Seasonal mean temperature

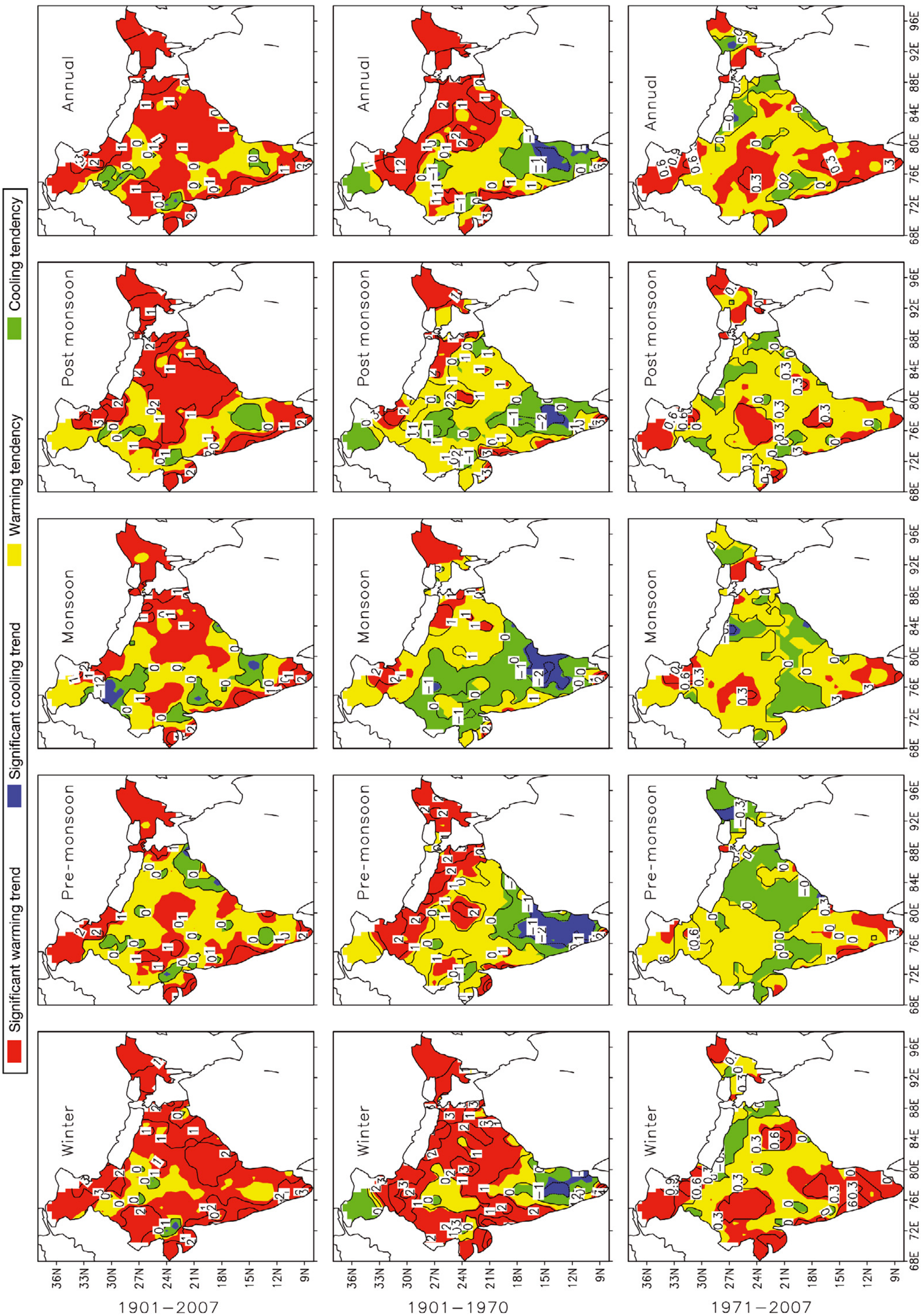

Fig. A2. Seasonal maximum temperature

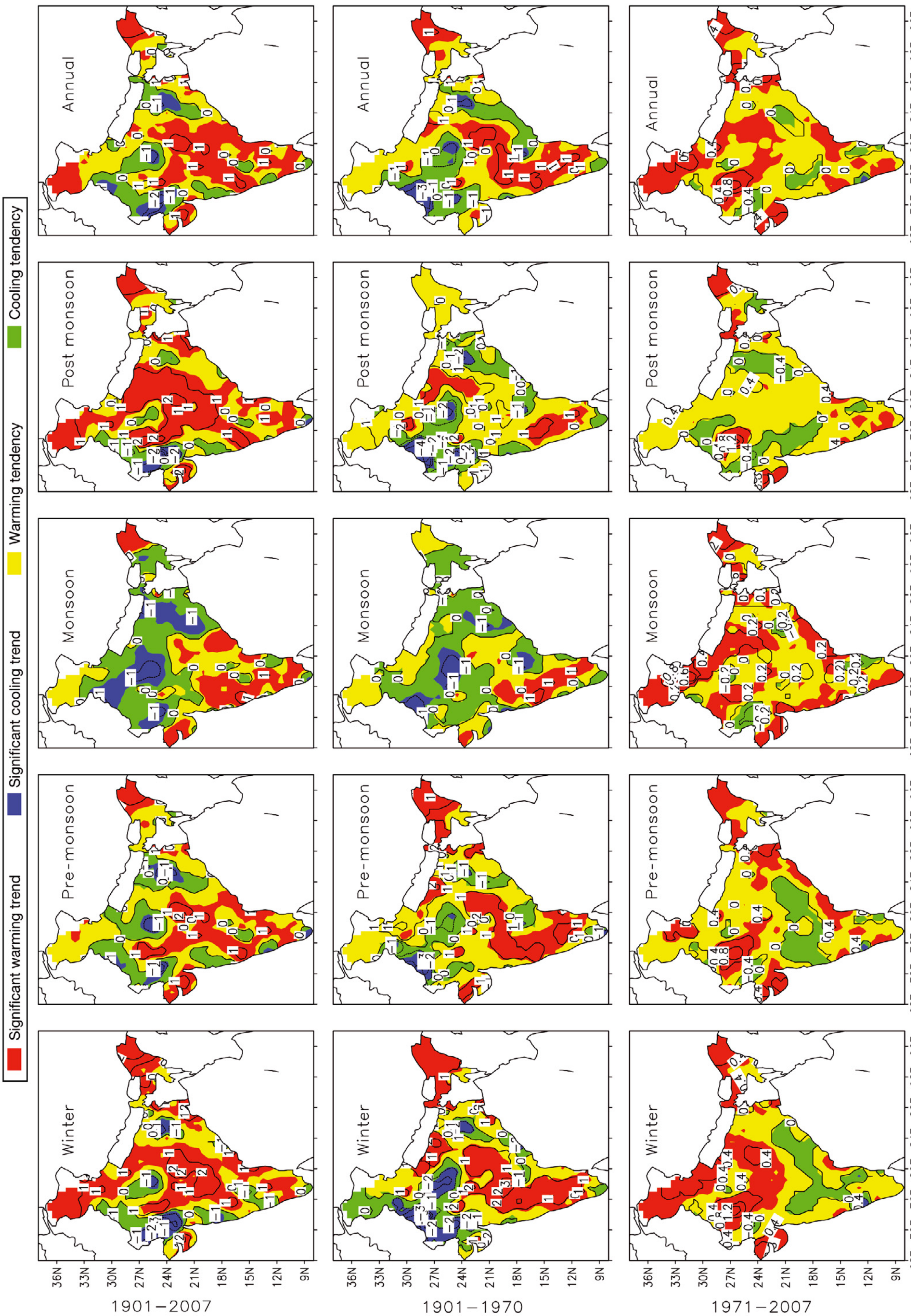

Fig. A3. Seasonal minimum temperature

Appendix 2. Composites of standardised temperature anomalies

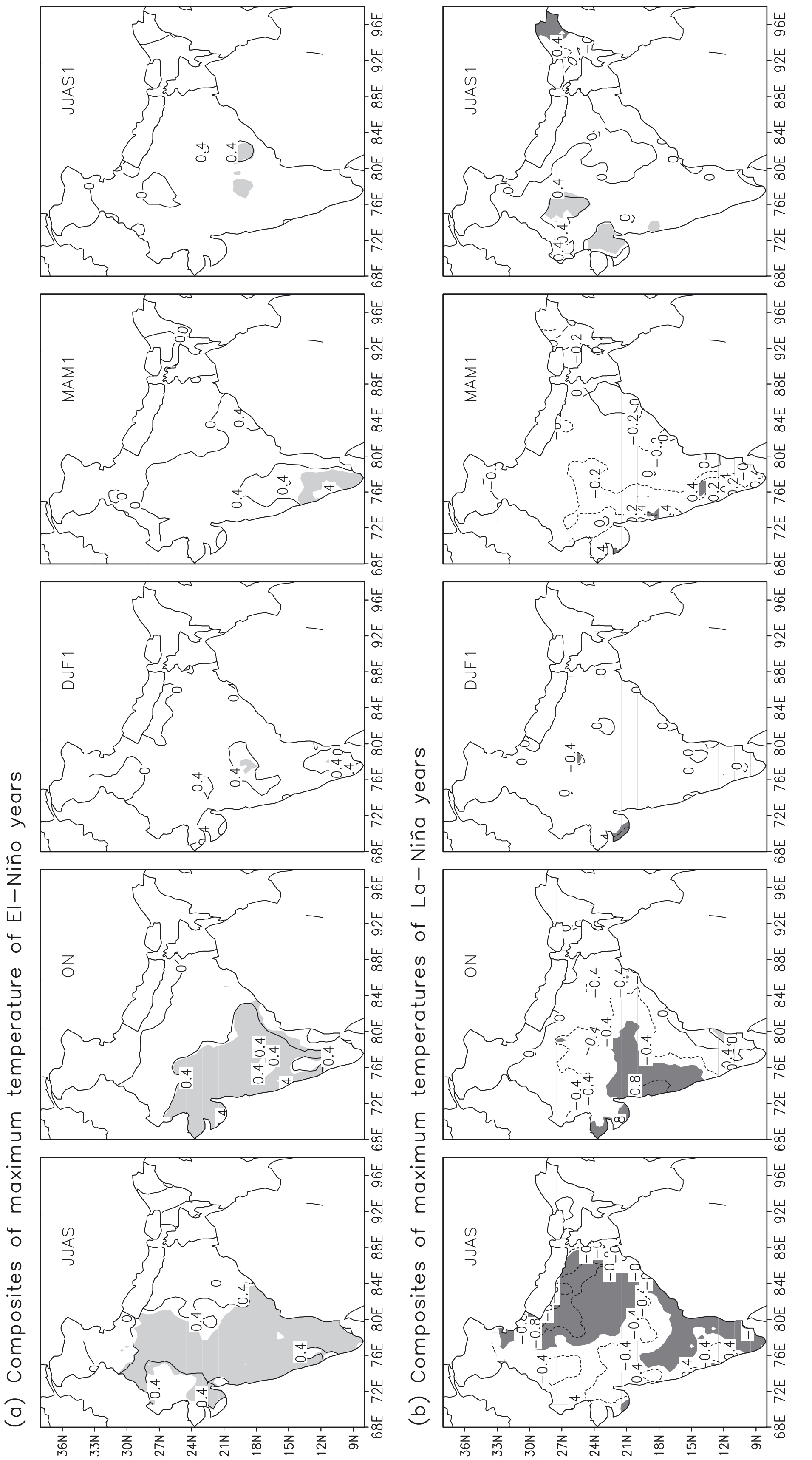

Fig. A4. Seasonal maximum temperature anomalies (°C) for (a) El Niño and (b) La Niña years. Shading indicates anomalies (midgrey: warm; dark grey: cold) significant at 5% level

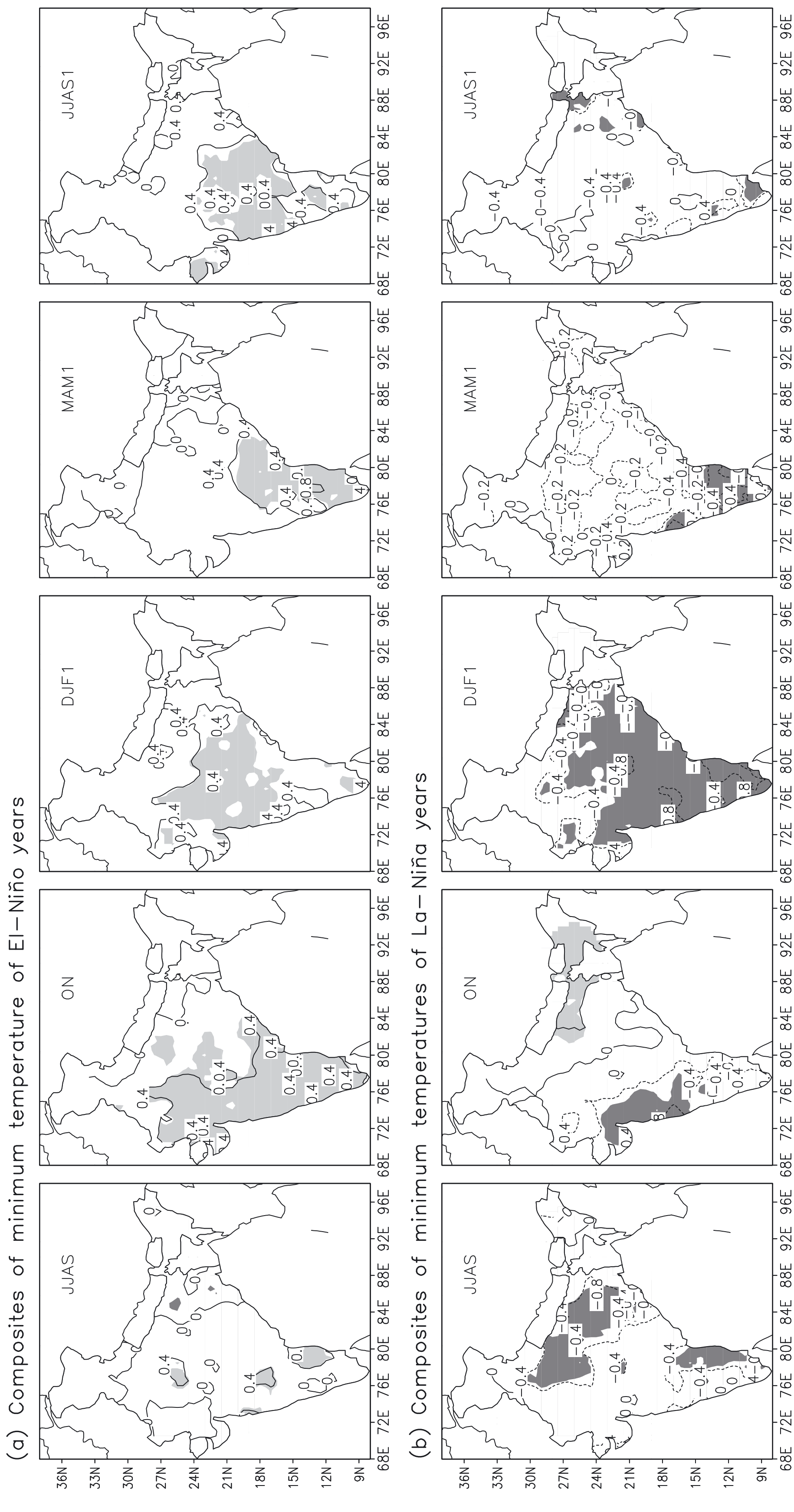

Fig. A5. As Fig. A4, but for seasonal minimum temperature anomalies (°C)

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