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Tropospheric temperature variation over India and links with the Indian summer monsoon : 1971-2000

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सार - विश्वस्तरीय ऊष्णीकरण के क्षेत्रीय पहलुओं पर लगातार बढ़ती हुई दिलचस्पी को देखते हुए भारत में क्षोभमंडलीय तापमान के देश-काल सापेक्ष परिवर्तनों की जानकारी अत्यंत महत्वपूर्ण है। इस अध्ययन में समुचित स्थानों पर स्थापित 19 रेडियोसौन्दे के स्टेशनों से 1971-2000 की अवधि के प्राप्त किए गए आँकड़ों के आधार पर धरातल तथा पाँच चुने हुए ऊपरी स्तरों अर्थात 850, 700, 500, 200 और 150 हैक्टापास्कल पर पाए गए मौसमी तथा वार्षिक माध्य तापमानों के परिवर्तनों की जाँच की गई है। इस शोध-पत्र में भारत में क्षोभमंडलीय तापमान के परिवर्तनों तथा ग्रीष्म मानसून की परिवर्तनशीलता, के प्रमुख दूर संपर्क प्राचल, एल-नीनों/दक्षिणी दोलन (ENSO) की भूमिका सहित इन दोनों के बीच परस्पर संबंधों का पता लगाने का प्रयास किया गया है।

इस शोध-पत्र में धरातल और पाँच क्षोभमंडलीय स्तरों के तापमानों का पता लगाने के लिए मौसमी तथा अखिल भारतीय वार्षिक माध्य तापमान की श्रृंखलाओं का विश्लेषण किया गया है। विभिन्न क्षोभमंडलीय स्तरों के तापमान के वार्षिक माध्य चक्रों से यह पता चलता है कि 850 हैक्टापास्कल तथा 150 हैक्टापास्कल के स्तरों पर मानसून ऋतु के तापमान की तुलना में धरातल पर मानसून पूर्व की ऋतु थोड़ी उष्ण होती है। जबकि सभी मध्यवर्ती स्तरों पर यह अपेक्षाकृत ठंडी होती है। वार्षिक माध्य तापमान में प्रति 10 वर्षों में क्रमशः धरातल और 850 हैक्टापास्कल के स्तर पर 0.18° से. तथा 0.3° से. की उष्णता का पता चलता है।

अधिक न्यून मानसून वर्षों के वर्षों की क्षोभमंडलीय तापमान की मिश्रित विसंगतियों से मई माह के दौरान सभी स्तरों पर अधिक न्यून सुस्पष्ट सकारात्मक (नाममात्र की) विसंगतियों का पता चलता है। डार्विन के मानसून पूर्व दाब का धरातल और 850 हैक्टापास्कल पर मानसून तापमान के साथ परस्पर सहसंबंध उल्लेखनीय रूप से सामान्य पाया गया है।

ABSTRACT. In the context of the ever increasing interest in the regional aspects of global warming, understanding the spatio-temporal variations of tropospheric temperature over India is of great importance. The present study, based on the data from 19 well distributed radiosonde stations for the period 1971-2000, examines the seasonal and annual mean temperature variations at the surface and five selected upper levels, *viz*., 850, 700, 500, 200 and 150 hPa. An attempt has also been made to bring out the association between tropospheric temperature variations over India and the summer monsoon variability, including the role of its major teleconnection parameter, the El Niño/Southern Oscillation (ENSO).

Seasonal and annual mean all-India temperature series are analyzed for surface and five tropospheric levels. The mean annual cycles of temperature at different tropospheric levels indicate that the pre-monsoon season is slightly warmer than the monsoon season at the surface, 850 hPa and 150 hPa levels, while it is relatively cooler at all intermediate levels. The mean annual temperature shows a warming of 0.18° C and 0.3° C per 10 years at the surface and 850 hPa, respectively.

Tropospheric temperature anomaly composites of excess (deficient) monsoon rainfall years show pronounced positive (negative) anomalies during the month of May, at all the levels. The pre-monsoon pressure of Darwin has significant positive correlation with the monsoon temperature at the surface and 850 hPa.

Key words – Tropospheric temperatures over India, Temperature trends, Monsoon rainfall - Temperature links, ENSO and Indian temperatures.

1. Introduction

Atmospheric temperature is probably the most widely used indicator of climate change, both on global/hemispheric and regional scales. Interest in temporal variations of temperatures over India started quite early, when sufficiently long instrumental data records became available. Pramanik and Jagannathan (1954) examined the trends of maximum and minimum temperatures of 30 Indian stations, and 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) reported with more data that the mean annual temperature increased by about 0.4° C/100 years in India during the 20 century. Kothawale (1992) reported that the mean annual maximum temperature has increased by about 0.5° C/100 years during the past century, while there was no systematic change in the minimum temperature. Srivastava *et al*. (1992) have 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 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.

While the surface temperature has been studied quite extensively, relatively few studies have been reported regarding the regional characteristics of tropospheric (including upper air) temperature variations. Angell and Korshover (1975) has pioneered the analysis of tropospheric temperature variations over the globe as well as for different climate zones and has been regularly updating his work until the recent period (Angell, 2000). Angell (1999), using global upper-air temperature data at 63 radiosonde stations, reported that globally the surface warmed relative to the 850-300 hPa layer in all the seasons except JJA, when the 850-300 hPa warming was slightly greater. Also, he observed that the surface warming was greater in the northern hemisphere than in the southern hemisphere, while in the 850-300 hPa layer the warming was greater in the southern hemisphere than in the northern hemisphere. Angell (2000) has also observed significant and positive lag correlation between Nino3 SST and the tropospheric (850-300 hPa) temperature of tropics, globe and north temperate zone, two seasons later. Weber (1995) has studied the seasonal variation of tropospheric (1000-300 hPa) temperatures over the northern hemisphere as well as different geographical regions during the period 1976-90, and found warming trend throughout the troposphere in all the regions. Later, Weber (1997) used the data for the 300 hPa temperature, during 1966-93, and observed warming over lower and middle latitudes but slight cooling over higher latitudes.

There have been very few studies dealing with tropospheric temperature variations over India. Rupa Kumar *et al*. (1987) have studied variation of tropospheric temperature over India during 1944-85, by considering the data at 10 radiosonde stations. They observed that the annual as well as seasonal all-India mean surface temperatures do not show appreciable trends during the period 1958-85. However, there was warming at the upper levels up to 200 hPa, particularly at the northern Indian stations, for the period 1944-58, and cooling thereafter. By using more number of Indian surface and radiosonde stations (475 surface stations, 31 radiosonde stations) for the period 1901-86 and 1951-86 respectively, Srivastava *et al*. (1992) have reported that the temperatures north of 23° N show a general decreasing trend, while the southern part of the country has been getting warmer, from surface to the middle troposphere.

Some studies had been made to understand the interaction between tropospheric temperature and Indian monsoon rainfall. Parthasarathy *et al*. (1990) observed that the tropospheric temperature during the pre-monsoon season over India is positively correlated with the subsequent monsoon rainfall. Singh and Chattopadhyay (1998), based on the data at 7 radiosonde station, reported significant positive correlation between the all-India tropospheric mean temperature (850-300 hPa) in May and the subsequent Indian monsoon rainfall.

The present study aims to extend and update the above analysis for India, to understand the nature of the temperature trends at different levels in the troposphere, over the past three decades. To provide a background to the temperature variability, the paper also presents the mean climatological features of surface and upper-air temperature distribution over India.

2. Data and analysis

Monthly mean surface air temperature data of 121 stations well distributed over India (Fig. 1) have been used in the present study, covering the period 1901-90. Rupa Kumar *et al*. (1994) discussed the quality aspects of this data set. To examine the spatial patterns of the surface temperatures other than those due to topographical changes, all the station data have been reduced to a constant level equal to the mean height (377.4 m) of all the 121 stations, using a lapse rate of 6.5° C/km. A similar approach was used earlier by Rao (1976).

For the upper-air temperatures, a network of 19 well distributed radiosonde stations having sufficient data length and relatively less missing values have been selected (Fig. 1). Such data for a well distributed network of stations are available for the period 1963-2000. However, it may be noted that there had been a change of instrumentation during this period, with possible consequences to the homogeneity of the data. The radiosonde instruments were changed during 1968-70 in India, when audio modulated type (AM-type) sondes were introduced at all the stations (India Meteorological Department, 1980). Prior to that, the northern Indian stations were using Chronometer type (C-type) and the southern stations Fan type sondes. This problem was noted by Rupa Kumar *et al.* (1987). Raj *et al.* (1987) have also discussed about the discontinuities in the temperature and contour heights resulting from the change of instruments at Indian radiosonde stations, and shown that the contour heights/temperatures reported by F-type sondes were lower than those reported by C-type sondes and that AM-type sondes reported still lower values. To avoid the inhomogeneity in the data sets caused by the instrumentation change, we have mainly used the uniform data sets of the period 1971-2000 for the tropospheric levels: *viz*., 850, 700, 500, 200 and 150 hPa. In this context, a matter of further concern is the existence of some inconsistencies in the mean fields of temperature, geopotential height and winds over the Indian aerological network, as brought out by Ananthakrishnan and Soman (1992) for the months July and August using data during the period 1978-80. They reported that the horizontal gradients in the mean fields of temperature and geopotential height between pairs of stations in the network showed several inconsistencies. However, it has been noticed that such problems are relatively more pronounced at the upper tropospheric levels (200 hPa and above) and further, these inconsistencies in terms of spatial patterns may not have a significant impact on the long term trends of spatially averaged temperatures.

The basic source of monthly mean surface temperature data is the National Data Center of the India Meteorological Department. The upper-air temperature data are taken from the Monthly Climatic Data for the World (NOAA/WMO). There were a few gaps in the data sets of monthly mean temperature and these missing values have been estimated from the data at neighbouring stations by regression techniques.

For a uniform spatial representation, the station data have been objectively interpolated onto a 1° × 1° grid for surface data and 2° × 2° grid for upper-air, with a 5° search radius, using an inverse squared distance weighted average algorithm. Near the surface, the spatial variability in the temperature is more than that at the upper levels (850-150 hPa), so more number (121) of stations are used for spatial patterns of surface temperature. Annual as well as seasonal mean temperature series are prepared for the seasons winter (DJF), pre-monsoon (MAM), monsoon (JJAS) and post-monsoon (ON). To keep the series consistent at different levels, the monthly and seasonal all-India mean surface air temperature series are also prepared on the basis of only the 19 upper-air stations. The all-India means are based on an arithmetic average of the land grid points, numbering 80 over the country.

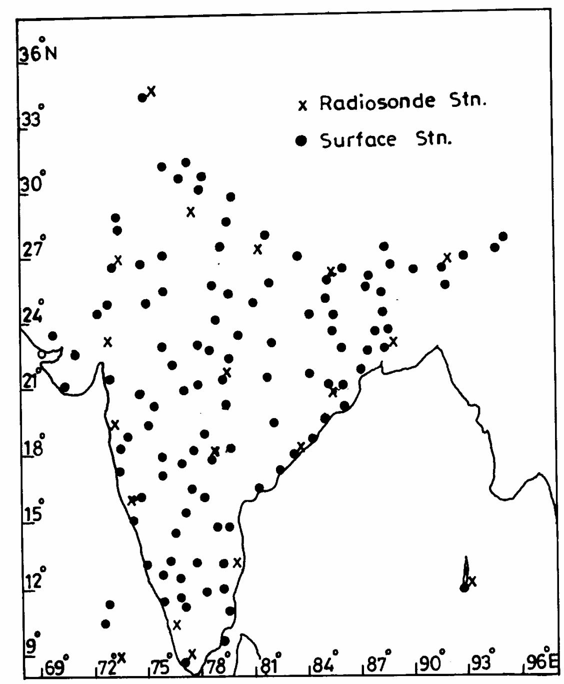
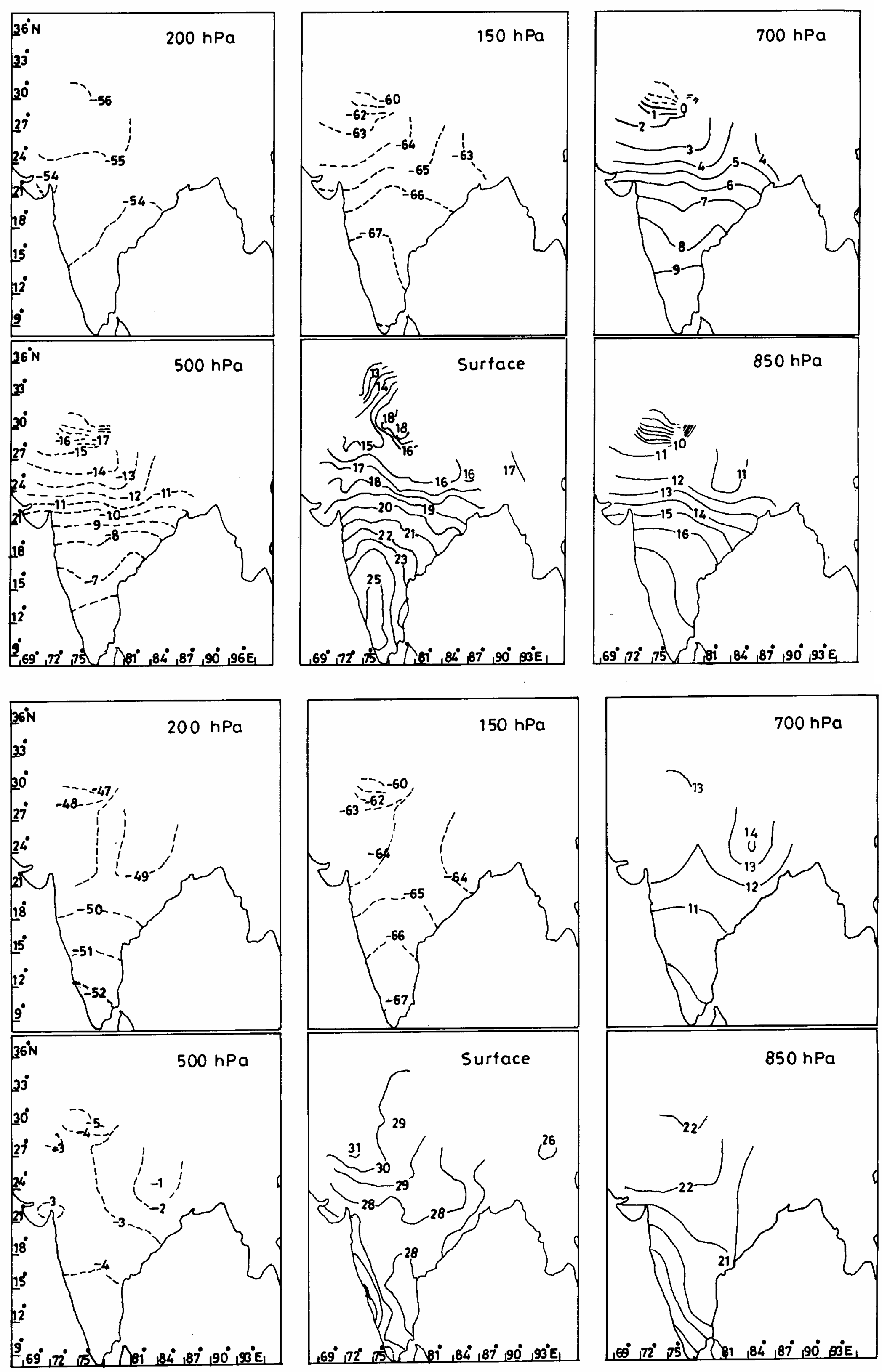


Fig. 1. Stations network of upper and mean surface air temperature (°C)

For examining the relationship between the all-India summer monsoon rainfall and the tropospheric temperatures, the all-India mean summer monsoon rainfall series, based on the IITM homogeneous monthly rainfall data set (http://www.tropmet.res.in), have been used for the period 1971-2000. (Parthasarathy *et al.* 1995). Darwin monthly mean sea level pressure data have been taken from Monthly Climatic Data for the world (NOAA/ WMO).

(a)

(b)



Figs. 2(a&b). Spatial patterns of (a) winter (DJF) mean temperature (°C) and (b) monsoon (JJAS) mean temperature (°C)

3. Mean spatial patterns of troposphere temperatures

In order to provide the necessary background to discuss the nature of tropospheric temperature trends, an attempt is made in this section to summarize the spatial patterns of seasonal mean temperatures at the surface and different tropospheric levels. The spatial patterns are based on the 19 stations for upper-air data during the period 1971-2000 and 121 stations for surface data during 1901-90. It may be noted that the surface temperatures are reduced to a common altitude, to remove spatial variation due to the topographical features of the region. Spatial patterns of surface and upper-air temperatures were presented earlier by Rao (1976) for the representative months of the four seasons. Here, we present the spatial patterns for the two most contrasting seasons winter (DJF) and monsoon (JJAS).

The mean surface air temperature in the winter season increases from about 13° C in the north to more than 25° C in the south. The isotherms are nearly parallel to the latitude over the north Indian plains. The highest temperature (>25° C) is observed over the southwestern parts of peninsular India [Fig. 2(a)]. Thus, one can perceive a northeast to southwest temperature gradient over the southern peninsula, which is associated with the northeast monsoon. The spatial patterns of temperature at 850 hPa are markedly similar to those at the surface. However, at 700 and 500 hPa levels, the isotherms are nearly latitude-dependent all over the country, with the temperatures increasing from north to south. At 200 hPa, the temperatures are nearly uniform all over the country. At 150 hPa, the temperature gradient is reversed, with the temperatures decreasing from north to south.

Consequent to the increased cloudiness and rainfall associated with summer monsoon, the surface temperature dramatically drops from the pre-monsoon (not shown) to the monsoon season all over the country [Fig. 2(b)]. Except for the warmer (>30° C) temperatures over the northwestern parts, the temperatures are nearly uniform around 28° C all over India. This pattern is a direct result of the monsoon rainfall distribution. The temperature gradients are south to north. The temperature generally increases from south to north, for all the levels from surface to 150 hPa. Unlike the other seasons, the north-south thermal gradient in the lower troposphere is fairly weak.

On the whole, some significant common features can be noted in all seasons. The temperature decreases from south to north at the levels surface to 200 hPa for the seasons winter, pre-monsoon and post-monsoon, whereas in monsoon season, the temperature gradient is reversed. At 150 hPa, temperatures increase from south to north in all seasons. The spatial patterns of temperatures are nearly similar at the surface and 850 hPa while those at 700 hPa are similar to the patterns at the 500 hPa level. At 200 hPa, the temperature is uniform except in the monsoon season. In the monsoon season, the temperature gradient is higher in the upper troposphere than in the lower troposphere.

4. All-India mean tropospheric temperature variations

The all-India mean monthly and seasonal surface and tropospheric temperature series are computed for the period 1971-2000 by taking the arithmetic average of the land grid points (numbering 80) over the country. These series are helpful to understand the large scale temperature variations at different levels. For the sake of comparison with the upper-air temperature series, the surface temperature series are also computed based on 19 stations.

4.1. *Annual cycle*

The annual cycles of tropospheric temperatures over India, represented by the all-India mean temperature at the surface and five upper levels, 850, 700, 500, 200 and 150 hPa are shown in Fig. 3. At the surface, the temperature increases from January and attains a peak in the month May, and later starts to decrease. However, the temperature remains nearly constant during the monsoon months and a marked drop to winter temperatures occurs only after October. Similar annual cycle of temperature is observed at 850 hPa. Higher up, at 700 hPa, 500 hPa, and 200 hPa, the annual peak of high temperatures gradually shifts towards the monsoon months (June-July). The temperature cycle is dramatically changed at 150 hPa, with the peak temperature occurring in April and the lowest temperature in October. At this level, however, the annual cycle is not pronounced.

The lowest temperatures of the year occur in winter at all the levels, except at the 150 hPa where they occur in the post-monsoon season (Table 1). The pre-monsoon and monsoon temperatures are nearly the same at surface and 850 hPa levels. While April and May are the hottest months of the year, the inclusion of the relatively cooler month March in computing pre-monsoon seasonal temperature brings the later closer with monsoon temperature. At the upper levels (700-200 hPa) there is significant temperature difference between these two seasons; the monsoon temperature is higher than the pre-monsoon temperature. At 150 hPa, the temperature cycle is markedly different from that at the lower levels and the highest temperatures are seen in the pre-monsoon season.

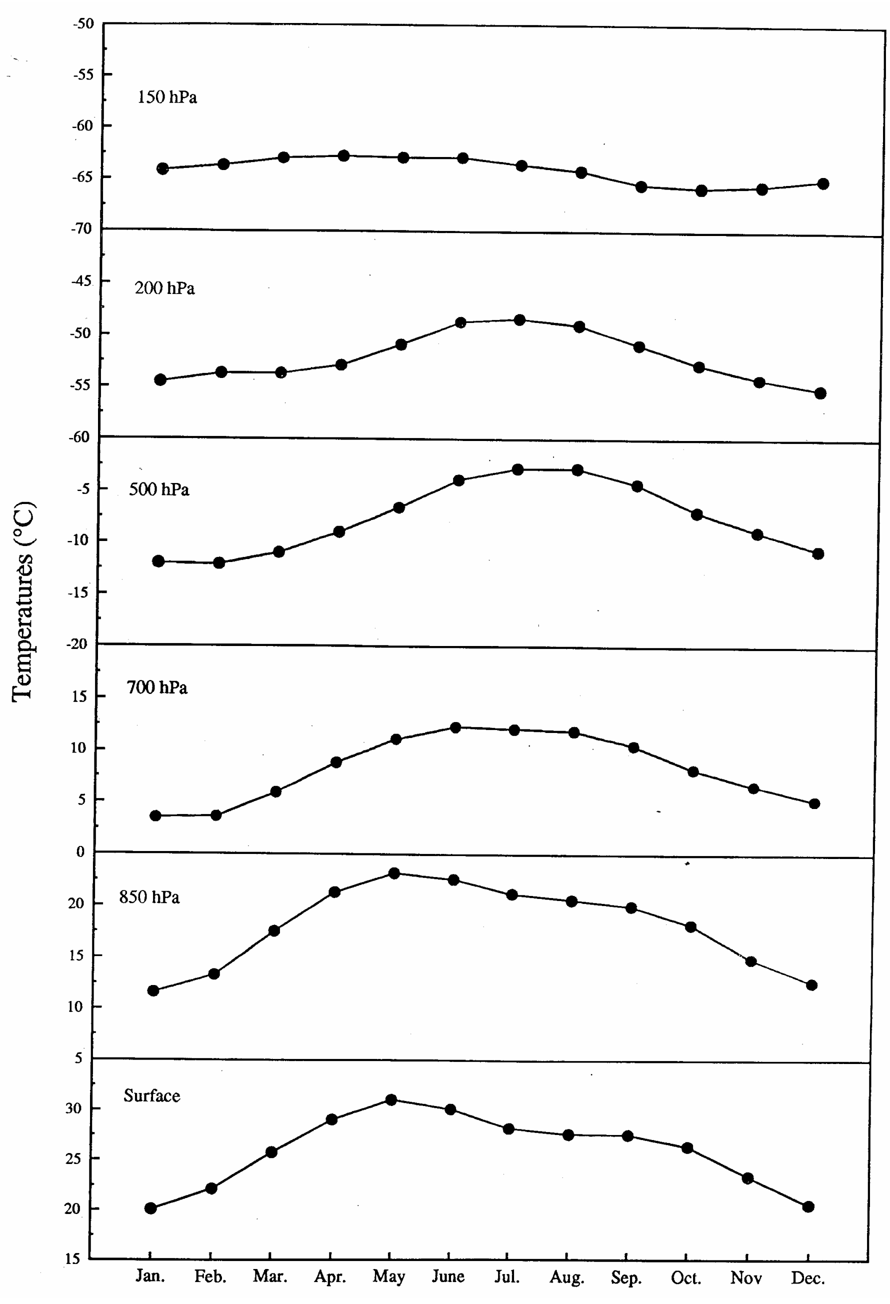


Fig. 3. Annual cycle of tropospheric temperature (°C) over India

During the pre-monsoon season, the Indian region is marked by clear skies, which, coupled with intense as well as increased solar radiation, results in high temperatures at the surface. In the monsoon season, the temperature is decreased due to the widespread precipitation over the region. In the 700-200 hPa layer the monsoon temperatures are higher than the pre-monsoon temperatures, obviously due to the release of large amount of latent heat associated with monsoon precipitation (Keshavamurty and Sankar Rao, 1992). This feature does not extend to the 150 hPa level.

5. Long term trends

All-India mean annual and seasonal tropospheric temperature series have been examined for long term

TABLE 1

Mean and standard deviations (SD) of seasonal/annual tropospheric temperatures over India (°C), during the period 1971-2000

Level	DJF		MAM		JJAS		ON		Annual	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Surface	20.9	0.4	28.6	0.4	28.4	0.3	24.8	0.5	26.0	0.3
850hPa	12.4	0.6	20.6	0.6	21.1	0.5	16.6	0.6	18.1	0.4
700hPa	4.0	0.7	8.6	0.7	11.7	0.6	7.4	0.7	8.3	0.5
500hPa	-11.7	0.8	-8.9	0.8	-3.5	0.7	7.9	0.8	-7.6	0.6
200hPa	-54.5	1.2	-52.5	1.2	-49.3	1.3	-53.5	1.3	-52.1	1.0
150hPa	-64.3	0.9	-62.9	0.9	-64.1	1.3	-65.7	1.1	-64.1	0.9

TABLE 2

Linear trend (°C /10 years) in seasonal/annual mean tropospheric temperatures during the period 1971-2000

	DJF	MAM	JJAS	ON	Annual
Surface	0.27**	0.03	0.17*	0.23	0.18*
850 hPa	0.23	0.16	0.34*	0.25	0.30*
700 hPa	0.29	0.30	0.50*	0.19	0.34
500 hPa	0.33	0.27	0.40	0.14	0.30
200 hPa	0.33	0.23	0.70	0.40	0.44
150 hPa	0.22	0.25	0.70	0.40	0.40

** Significant at 1% level, * Significant at 5% level

variations. The trend is quantified by the slope of a simple linear regression line fitted to each of the series against time and expressed as trend per 10 years. The statistical significance of trend is assessed by means of F-ratio, after taking into account the autocorrelation, if any, present in the series (Wigley and Jones, 1981).

From surface to 500 hPa, the annual mean temperature of 1963-2000 shows increasing trend. However, the trend is statistically significant only at the surface [Fig. 4(a)]. At 200 hPa and 150 hPa levels the temperature shows decreasing trend, but the trend values are not significant. However, keeping in view the fact that the time series may contain possible inhomogeneities due to the instrumental changes, we have considered the period 1971-2000 having uniform instrumentation. During this period the mean annual temperatures shows warming trend at all the levels from surface to 150 hPa, but the trends are significant only at the surface and 850 hPa [Fig 4(a) and Table 2]. From surface to 200-150 hPa, the variability in annual temperatures gradually increases. The standard deviation (S.D.) of temperature series ranges from 0.3 at the surface to about 1 at 200-150 hPa (Table 1). The increase in S.D. with height is also seen in the seasonal mean temperatures. An interesting feature of the temperature series at different levels is the occurrence of a relatively cooler period during 1975-85 at all levels from 850 hPa and above. This feature is seen in annual as well as seasonal mean temperature series. The linear trend values at surface to 150 hPa for all the seasons are presented in Table 2.

The seasonal mean all-India tropospheric temperature series are presented for the period of uniform instrumentation, *viz*., 1971-2000, in Figs. 4(b-e). During the winter season significant warming (0.27° C/10 years) is observed at the surface [Fig. 4(b)]. The temperature shows increasing trend at all the upper levels also, but the trend values are not statistically significant. In the pre-monsoon season, the temperature is practically trendless at the surface whereas the upper air temperatures show warming trend but not significant [Fig 4(c)]. During the monsoon season, the temperature shows significant increasing trend at the surface, 850 hPa and 700 hPa by 0.17° C, 0.34° C and 0.5° C/10 years respectively [Fig. 4(d)]. In the upper troposphere (500-150 hPa) also

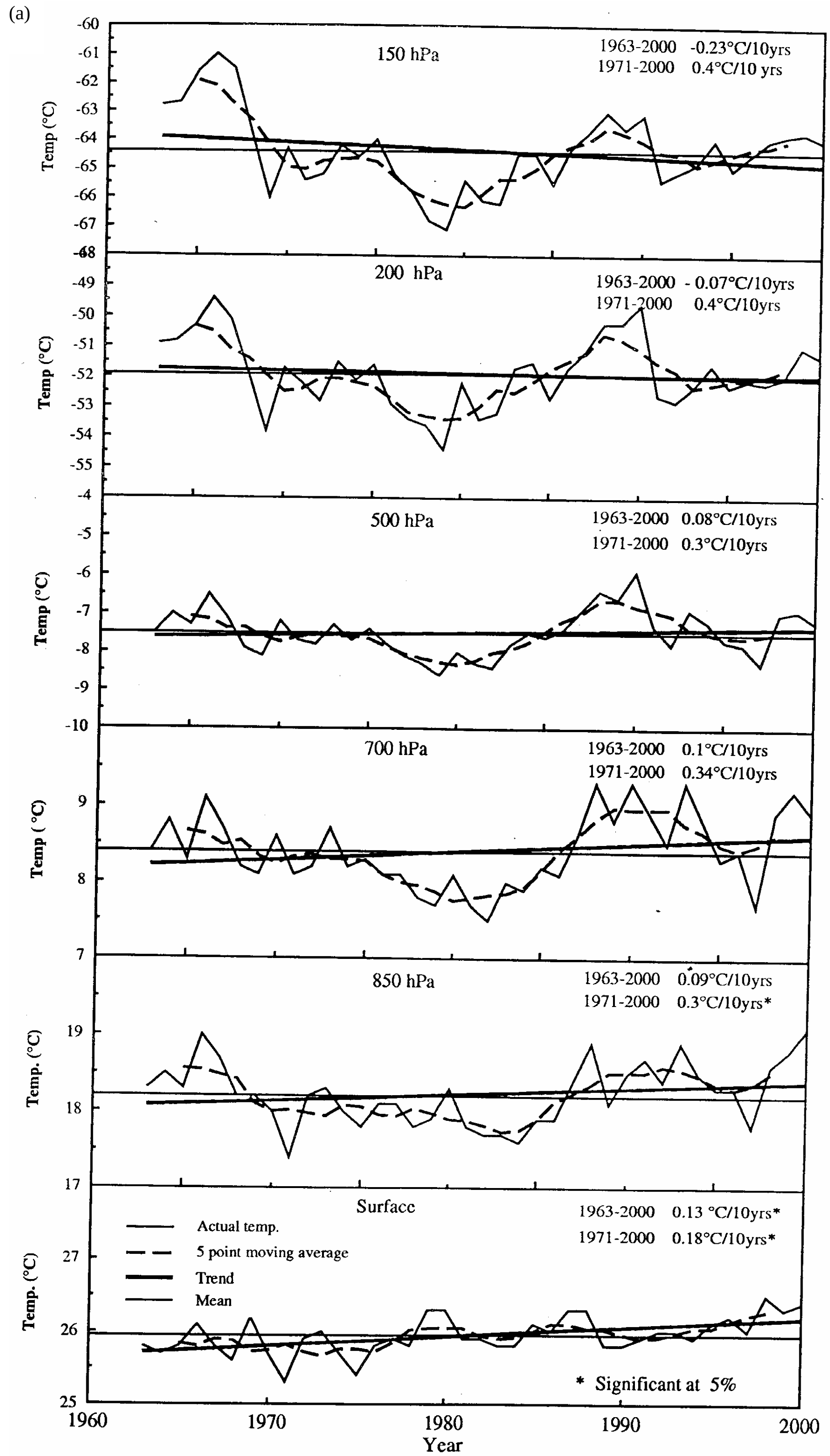


Fig. 4(a). Variation of annual mean tropospheric temperature (°C) over India

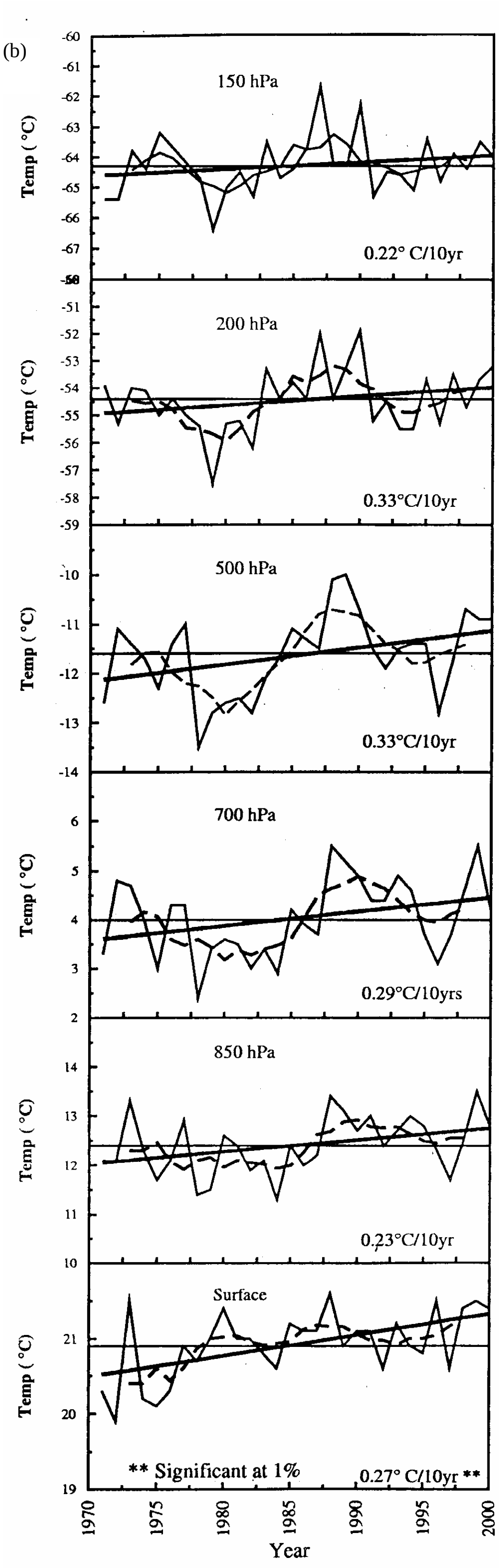


Fig. 4(b). Variation of winter (DJF) mean tropospheric temperature (°C) over India

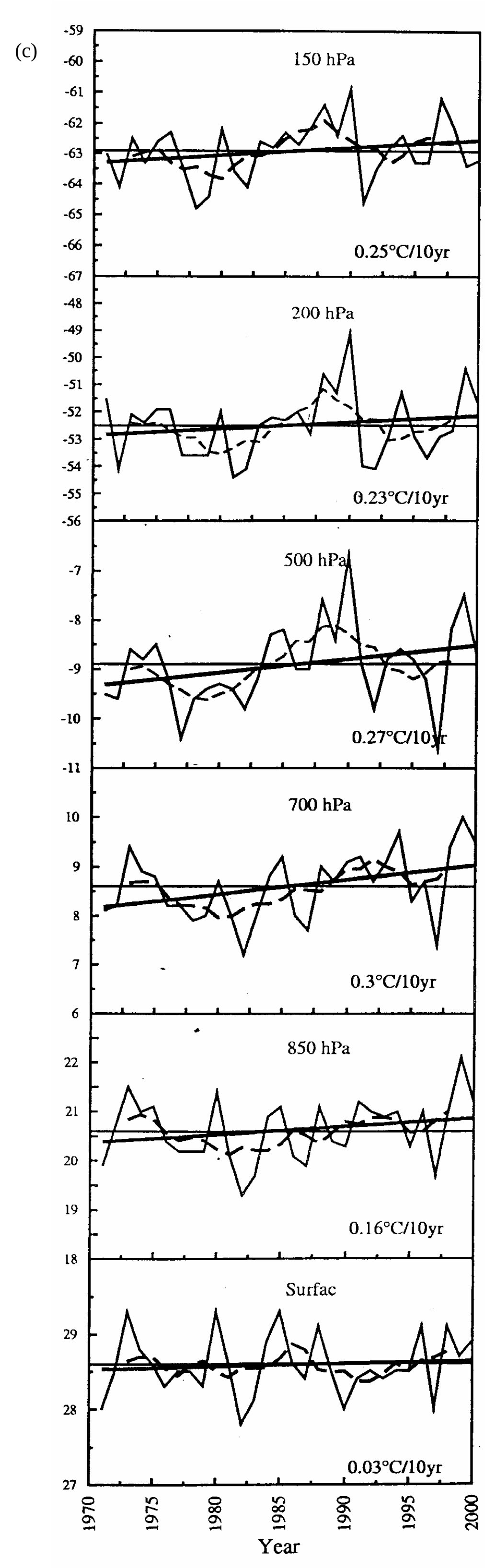


Fig. 4(c). Variation of pre-monsoon (MAM) mean tropospheric temperature (°C) over India

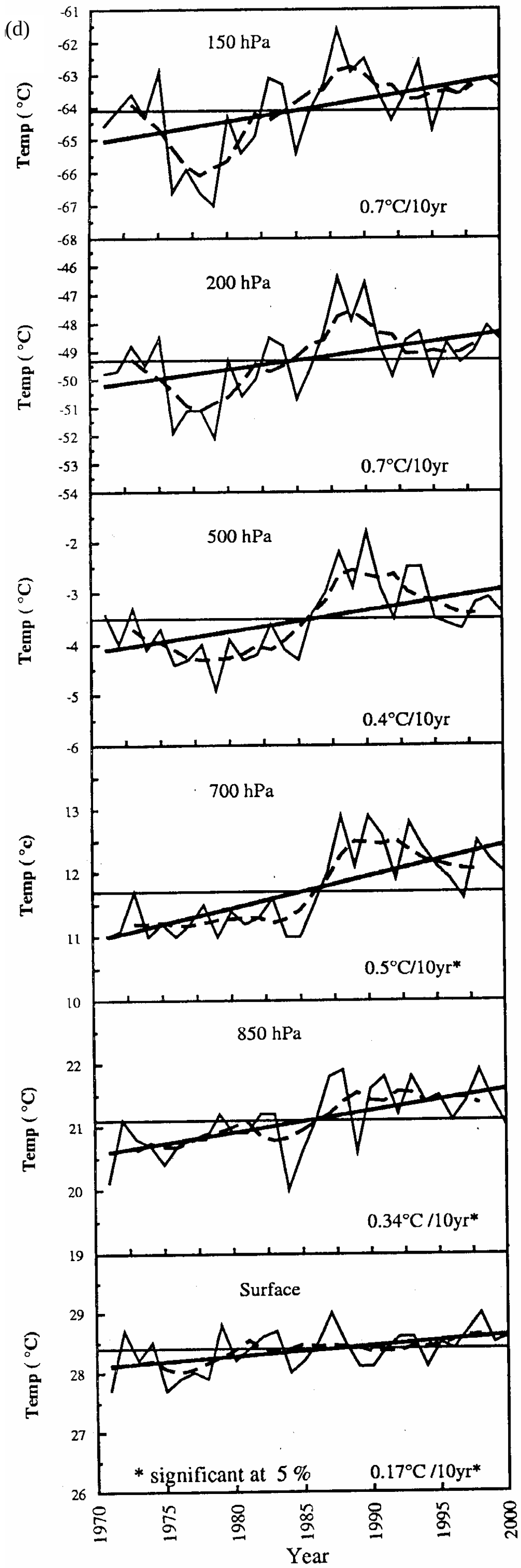


Fig. 4(d). Variation of monsoon (JJAS) mean tropospheric temperature (°C) over India

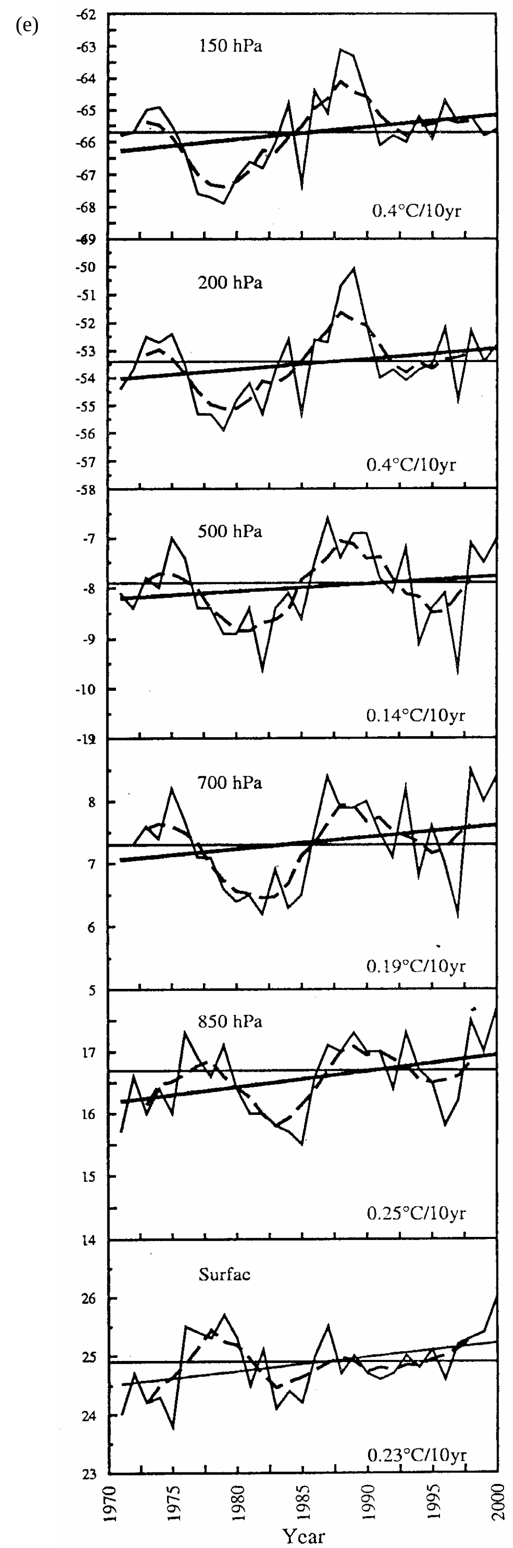


Fig. 4(e). Variation of post-monsoon (ON) mean tropospheric temperature (°C) over India

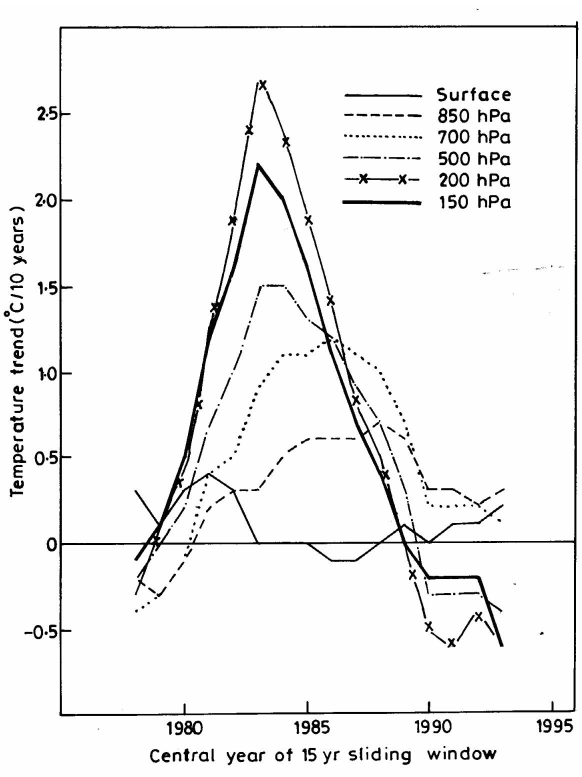


Fig. 5. 15-years sliding trends at the tropospheric levels (Surface to 150 hPa)

the temperature shows increasing trend but the trend values are not statistically significant. In the post-monsoon season, the temperature at all the levels shows the warming trend but not significant [Fig. 4(e)].

On the whole, the all-India annual mean surface temperature has increased by 0.18° C/10 years in the recent period (1971-2000). The surface warming is statistically significant in winter and monsoon seasons. Hingane *et al*. (1985) have noticed significant warming trend (1901-82) in the all-India mean annual and seasonal temperatures during winter, pre-monsoon and post-monsoon seasons, but the monsoon temperature displayed no trend when seen over a long period of time. Their analysis was based on 73 well spread stations over India for the period 1901-82. The results of the present study indicate that the monsoon temperatures have shown significant trend over the past three decades. However, differences in the data periods and the considerably less number of stations used in the present study for trend analysis possibly might have caused the differences in trends.

The temperature time series from 850 hPa to 150 hPa levels show conspicuous low-frequency variations on a decadal scale [Figs. 4(a-e)]. These variations can have important consequences to temperature trends in different sub-periods. Considering this, secular variations in the annual mean temperature trend have been examined by means of the 15-year sliding trends at different levels (Fig. 5). The trends over sliding periods clearly indicate that there have been substantial changes not only in the magnitudes of the trends, but also in their direction. In general, the surface temperature has shown warming trend in the beginning and end of data period, with near-zero or even slight negative trends in the intervening periods, *viz*., from the years centered at 1982 to 1988. The levels 850 and 700 hPa show warming trends throughout the data period, except some cooling trend in the beginning. However, the magnitudes of warming trend substantially dropped down near the end of the data period. A remarkable feature of the trends in the upper troposphere (500-150hPa) is their variation being in phase. The temperature at these levels shows a dramatic increase in warming trend in the beginning of the data period, up to the period centered around 1982. Subsequently, the trend rapidly dropped and changed direction into cooling trend during the later part of the data period. On the whole, the upper-air temperature trends are nearly out of phase with lower tropospheric temperatures. Surface warming is generally associated with upper cooling in the beginning and end of the data periods. In the intervening period, the sudden upper tropospheric warming is followed by a dampening of surface warming and even cooling. These low frequency variations may be possibly a due to a complex interaction between possible influences related to greenhouse effect and sudden events of climate significance like volcanic eruptions.

6. Relationship between tropospheric temperature and summer monsoon variability

The monsoon is primarily a thermally forced phenomenon and as such any year-to-year variation in the asymmetric heating pattern over the regional/planetary scale is likely to influence the performance of Indian summer monsoon. In view of this, we have also made a detailed examination of the relationship between Indian monsoon rainfall and surface as well as upper air temperatures over the Indian region.

6.1. *Temperature composites for extreme monsoon situations*

Monthly and seasonal tropospheric temperature anomalies (standardized) composites of excess and deficient monsoon years are examined to bring out the association between monsoon variability and tropospheric

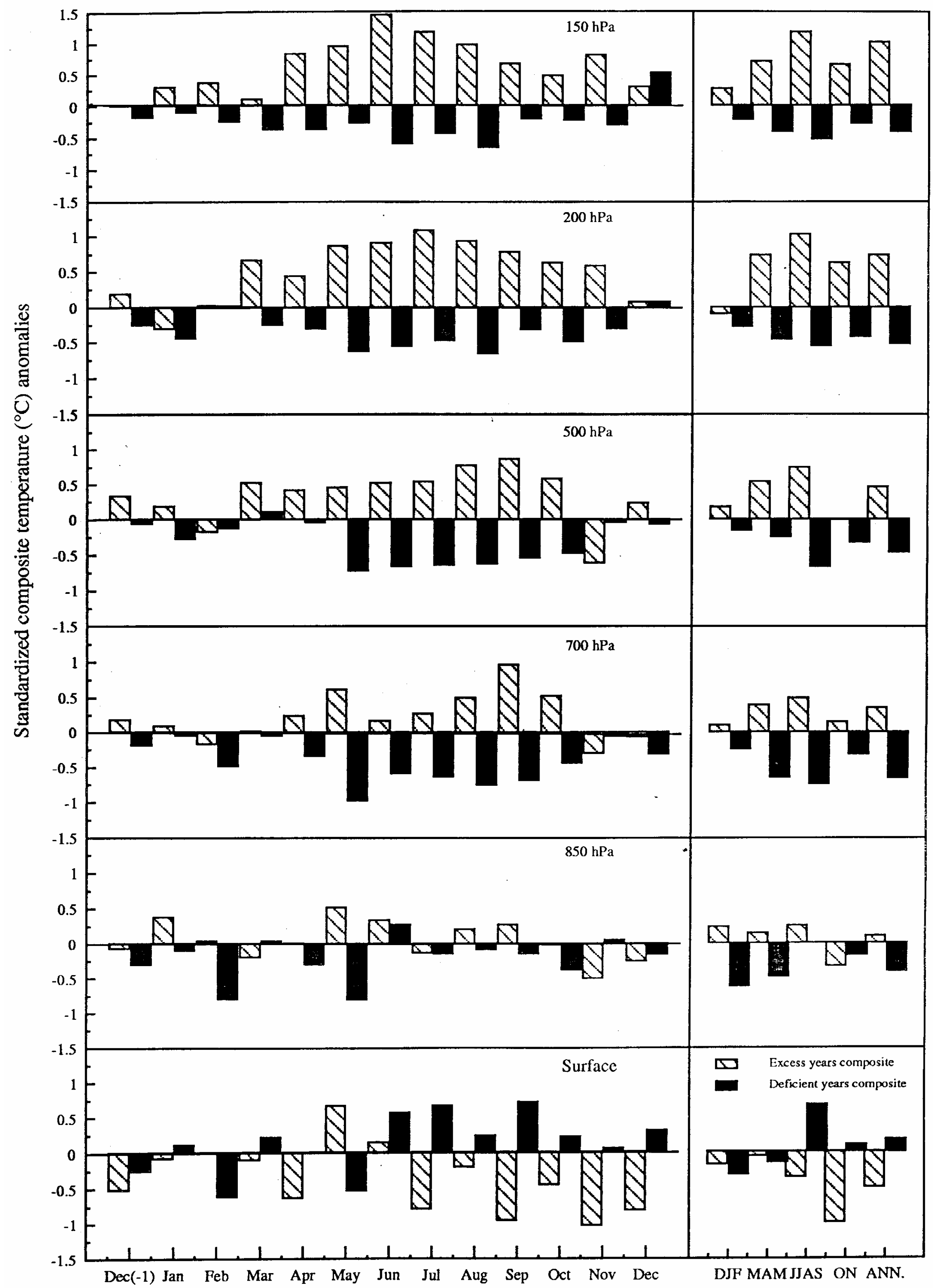


Fig. 6. Tropospheric temperature (°C) composites of extreme (excess and deficient) monsoon situations for previous year (December -1), present year (January to December and DJF to ON)

TABLE 3

Correlation coefficients between all-Indian monsoon rainfall and tropospheric temperature (1971- 2000)

	ON (lag-3)	DJF (lag -2)	MAM (lag -1)	JJAS (lag 0)	ON (lag +1)	DJF (lag +2)	MAM (lag+3)
Surface	0.27	0.11	0.07	-0.61**	-0.34*	-0.55**	-0.35*
850hPa	0.31	0.23	0.09	-0.09	-0.14	-0.25	-0.21
700hPa	0.15	0.09	0.27	0.38*	0.06	-0.06	-0.12
500hPa	0.03	0.05	0.23	0.44*	0.09	0.03	-0.05
200hPa	0.07	0.07	0.42*	0.39*	0.25	-0.16	-0.15
150hPa	0.06	0.16	0.44*	0.36*	0.20	-0.29	-0.30

** Significant at 1% level, * Significant at 5 % level

temperature variability (Fig. 6). The excess monsoon years considered for composites are 1975, 1983, 1988 and 1994 while the deficient monsoon years are 1972, 1974, 1979, 1982, 1985, 1986, 1987. During the deficient monsoon situations, at the surface, the temperatures are below normal during winter and pre-monsoon seasons and above normal during the monsoon and post-monsoon seasons, whereas at all the upper levels, the temperatures are below normal during all the seasons, with the cooling more pronounced in the monsoon season at middle and upper levels (700 to 150 hPa). This is possibly associated with decrease in latent heat released during the deficient monsoon season.

In excess monsoon situations, at the surface, temperature is slightly below normal during winter and near normal in pre-monsoon season but considerably below normal during monsoon and post-monsoon seasons. However, at all the upper levels from 850 to 150 hPa the temperatures are above normal in all the seasons, except at 850 hPa in the post monsoon season. At all these levels, the highest composite temperature anomaly is observed during the monsoon season, whose magnitude increases with height. So far as monthly temperature composites are concerned, it is interesting to note that the pre-monsoon temperature anomaly of May month is positive (negative) during the excess (deficient) monsoon year, at all the levels from surface to 150 hPa. This aspect can have potential applications for the seasonal forecasting of the Indian summer monsoon rainfall.

6.2. *Correlation between tropospheric temperature and all-India monsoon rainfall*

To understand the relationship between all-Indian summer monsoon rainfall and tropospheric temperatures, the all-India summer monsoon (JJAS) rainfall series has been correlated with surface as well as tropospheric temperature of different seasons. Detrended series are used in the computations of correlation coefficients. To examine lead/lag relationships between the two parameters, correlation with the seasonal mean temperatures up to three seasons before and after the monsoon season, have been worked out. There is a strong negative simultaneous correlation between all-India mean rainfall and all-India surface temperature during the monsoon season (Table 3). This negative correlation persists through all the subsequent seasons up to the pre-monsoon season of subsequent year. This can be one of the features associated with the quasi biennial cycle of the coupled monsoon system (Meehl, 1994). The correlations with 850 hPa temperatures are similar to those with the surface temperature, but with reduced magnitudes. While the correlations between lower tropospheric temperatures (surface and 850 hPa) and all-India monsoon rainfall are negative, the correlations are positive with the temperatures of middle and upper tropospheric levels, *i.e.*, 700 hPa to 150 hPa. It is interesting to see that the correlations between monsoon rainfall and the pre-monsoon season temperatures are positive throughout the troposphere, and significant at 200 hPa and 150 hPa levels. Similar correlations were also noticed by Parthasarathy *et al*. (1990) with data from limited number of stations. While the negative simultaneous correlations during the monsoon season are confined initially to the lower tropospheric levels, the negative correlations gradually extend to the upper levels in the subsequent seasons, possibly reinforcing the mechanisms of biennial cycle in the monsoon system as proposed by Meehl (1994). In this connection, it may also be noted that the correlation coefficients of monsoon rainfall with the previous year's post-monsoon temperatures at surface and 850 hPa are positive and close to significant levels.

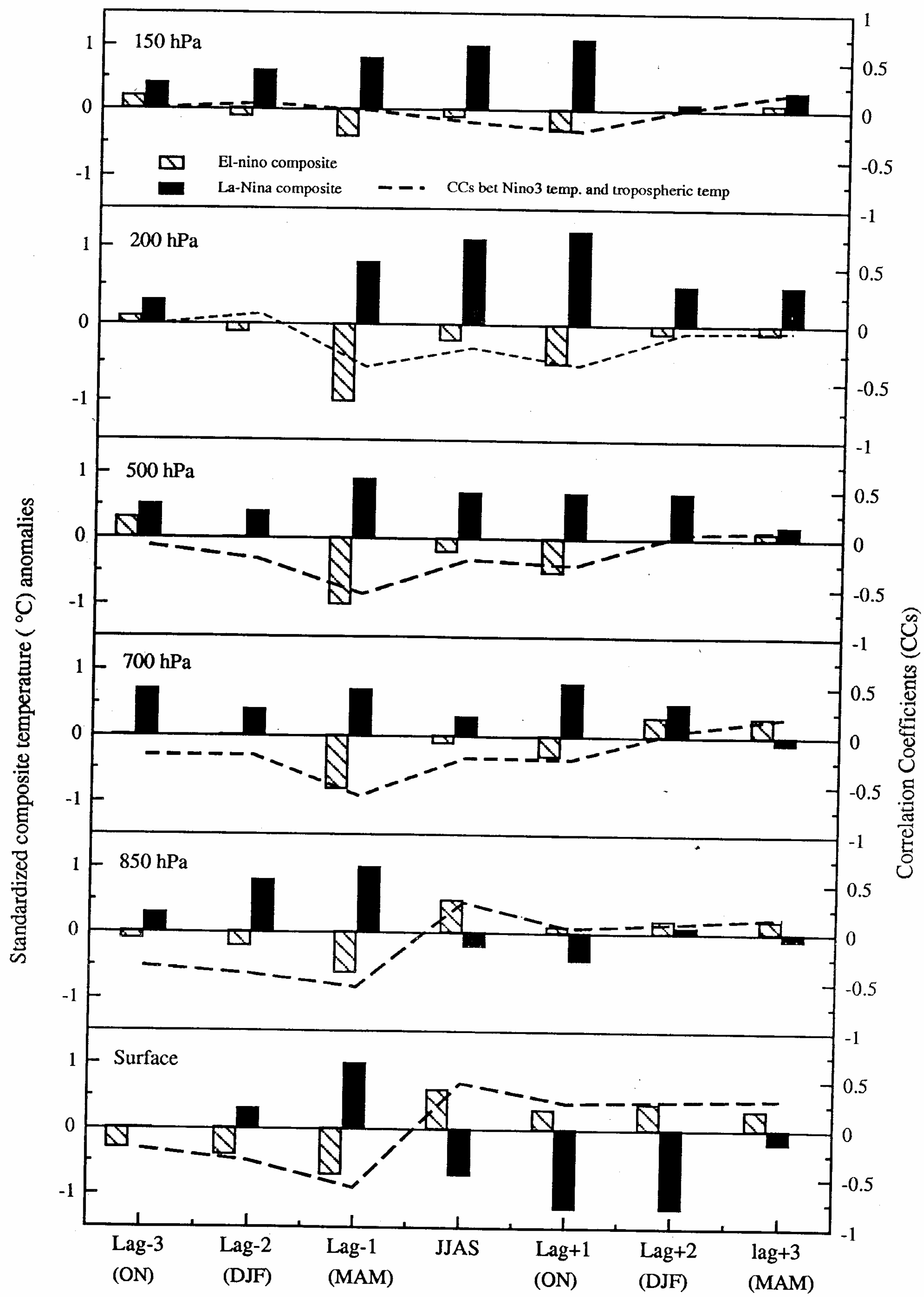


Fig. 7. El-Nino/La-Nina years composites of tropospheric temperatures for different seasons (lag-3 to lag+3) and correlation between JJA-Nino3 SST and seasonal (lag-3 to lag+3) tropospheric temperatures

TABLE 4

Correlation coefficients between JJA Nino3 SST and tropospheric temperature (1971-2000)

	ON (lag-3)	DJF (lag -2)	MAM (lag -1)	JJAS (lag 0)	ON (lag +1)	DJF (lag +2)	MAM (lag+3)
Surface	-0.21	-0.33	-0.60**	0.47**	0.27	0.29	0.31
850hPa	-0.34*	-0.42*	-0.55**	0.31	0.05	0.10	0.16
700hPa	-0.20	-0.20	-0.61**	-0.22	-0.23	0.06	0.20
500hPa	-0.08	-0.21	-0.56**	-0.21	-0.27	0.05	0.09
200hPa	0.00	0.09	-0.37*	-0.20	-0.35	-0.06	-0.05
150hPa	0.01	0.06	-0.01	-0.13	-0.21	0.02	0.19

** Significant at 1% level, * Significant at 5 % level

7. Tropospheric temperatures over India and El-Niño/Southern Oscillation (ENSO)

A large part of the interannual variability of monsoon rainfall is linked with El-Niño/Southern Oscillation (ENSO), a coupled ocean atmospheric phenomenon in the Pacific Ocean through the large scale displacement of east-west Walker circulation in the tropics (Walker, 1918, Pant and Rupa Kumar, 1997). ENSO has also been linked to seasonal precipitation and temperature anomalies the world over (Ropelewski and Halpert, 1987). Angell and Korshover (1983) have reported that the global temperature variation in the surface-100 hPa layer had been strongly influenced by the Southern Oscillation phenomenon, during the period 1958-81. In view of the profound impact of ENSO on the monsoon rainfall and possibly on the seasonal temperature anomalies, an attempt has been made here to examine the relation between ENSO and the tropospheric temperatures over India.

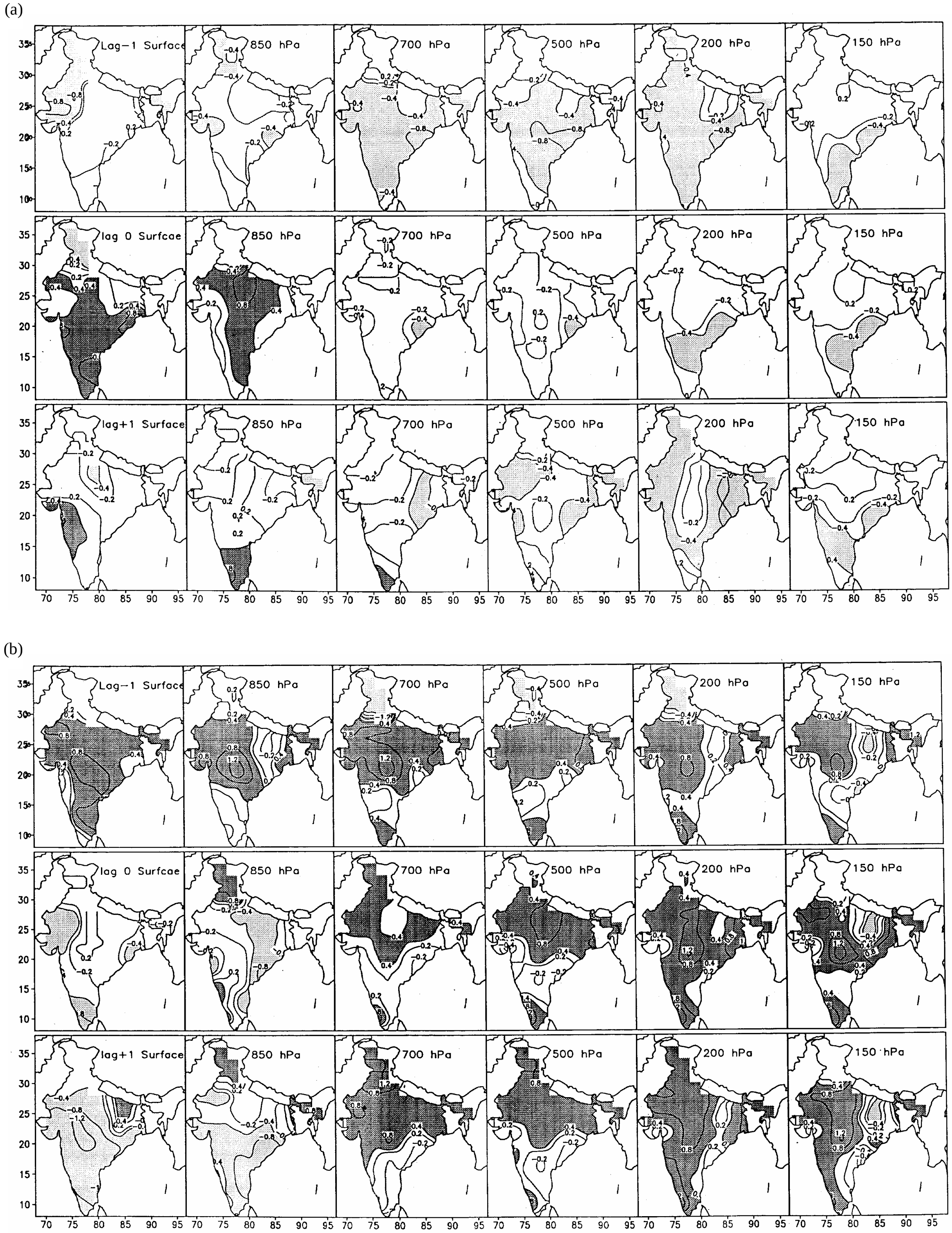
7.1. *Association between Nino3 SST and Indian tropospheric temperatures*

The association between seasonal tropospheric temperature of three seasons before and after the monsoon season during the El-Nino/La-Nina years and lag/lead correlations between JJA Nino3 SST and seasonal tropospheric temperature has been examined by applying the technique of superposed epoch analysis. Similarly the spatial patterns of composite temperature (surface to 150 hPa) of three seasons before and after the monsoon season of El-Nino/La-Nina events are examined.

By considering the seven El-Nino years *i.e.* 1972,1976,1982,1987, 1991, 1992, 1997 and three La-Nina years *i.e.*, 1973, 1983, 1988, the composite values of standardized tropospheric temperature have been computed for the seasons lag-3 (ON), lag-2 (DJF), lag-1 (MAM), lag-0 (JJAS), lag+1 (ON), lag+2 (DJF) and lag+3 (MAM) . The El-Nino (La-Nina) composite anomalies of tropospheric temperature are negative (positive) during the three seasons before monsoon season and positive (negative) during monsoon as well as all the subsequent seasons up to pre-monsoon of subsequent year, at surface and 850 hPa. At 700 to 150 hPa levels, the composites are similar to those at the lower levels upto the pre-monsoon season, but, there is no reversal of the signs of composites during and after the monsoon season noted at the lower levels (Fig 7).

Fig. 7 also includes the correlation coefficients (CCs) between JJA Nino3 SST and seasonal (lag-3 to lag+3) tropospheric temperature at all the six levels from surface to 150 hPa for the period 1971-2000. There is a pronounced negative relationship between tropospheric (surface-850hPa) temperature of three seasons prior to the monsoon and JJA Nino3 SST, and the relationship becomes positive from monsoon to successive year pre-monsoon (Fig 7). A conspicuous feature of the correlation of Nino3 SST with the Indian tropospheric temperatures is the statistically significant negative CCs during the pre-monsoon season (lag-1) throughout the tropospheric column (surface-200 hPa) while the CCs are significant and positive only near the surface during the monsoon season (Table 4). The lag/lead El-Nino and La-Nina composite tropospheric temperatures and lag/lead correlation between JJA-Nino3 SST and seasonal tropospheric temperature are in the same phase (Fig 7), indicating that the correlations are substantially influenced by the El-Nino/La-Nina events.

The spatial patterns of El-Nino/La-Nina composite temperature anomalies (standardized) for lag-1, lag 0 and



Figs. 8(a&b). Spatial patterns of (a) El-Nino years composites of tropospheric temperature for different seasons (lag-1, lag 0 and lag+1) and (b) La-Nina years composites of tropospheric temperature for different seasons (lag-1, lag 0 and lag+1). Dark/light shading indicates warm/cool region

TABLE 5

Correlation between Darwin sea-level pressure and Indian tropospheri temperatures (1971-2000)

	Darwin Pressure, DJF *vs.*				Darwin Pressure, MAM *vs.*			
Temp.	DJF	MAM	JJAS	ON	DJF	MAM	JJAS	ON
Surface	0.22	-0.02	0.26	-0.12	-0.15	-0.36*	0.54**	0.21
850 hPa	-0.04	-0.15	0.37*	-0.03	-0.23	-0.34*	0.59**	0.15
700 hPa	-0.16	-0.06	0.40*	0.11	-0.13	-0.40*	0.17	-0.12
500 hPa	-0.12	0.13	0.23	0.10	-0.24	-0.44*	0.05	-0.14
200 hPa	0.14	-0.06	0.21	0.09	-0.21	-0.50*	-0.10	-0.27
150 hPa	0.28	0.06	0.14	-0.02	-0.03	-0.15	-0.03	-0.18
	Darwin Pressure, JJA *vs.*				Darwin Pressure, SON *vs.*			
Temp.	DJF	MAM	JJAS	ON	DJF	MAM	JJAS	ON
Surface	-0.26	-0.50**	0.28	0.19	-0.30	-0.62**	0.20	0.24
850 hPa	0.02	-0.35*	0.30	0.05	-0.27	-0.50**	0.26	-0.05
700 hPa	0.16	-0.35*	0.01	-0.27	-0.11	-0.53**	-0.12	-0.50**
500 hPa	0.09	-0.37*	0.04	-0.35	-0.16	-0.51**	-0.11	-0.55**
200 hPa	0.04	-0.16	-0.04	-0.37	-0.25	-0.34	-0.23	-0.55**
150 hPa	-0.04	0.11	-0.01	-0.17	-0.14	-0.16	-0.20	-0.35*

** Significant at 1% level   * Significant at 5% level

lag+1 are also considered for further examination [Fig. 8(a)]. It is observed that during El-Nino events, warming is observed during the monsoon season (lag-0) at the surface and 850 hPa over a large part of the country, and it persists in the following season (lag+1) over a small region over the western peninsula. [Fig. 8(a)]. Considerable cooling is seen at 700 hPa to 200 hPa during pre monsoon season of El-Nino events. The spatial patterns of La-Nina composites of temperature are almost opposite to those of El-Nino composites [Fig. 8(b)]. El-Nino (La-Nina) events are generally associated with deficient (excess) rainfall in monsoon season, over India. Earlier studies have shown significant simultaneous association between the monsoon rainfall over India and ENSO indices (Pant and Parthasarathy, 1981). Given the inverse relationship between the rainfall and lower tropospheric temperature during the monsoon season (section 6.2), the spatial patterns of the El-Nino/La-Nina composites are consistent with the well known ENSO-monsoon association.

7.2. *Relationship between Indian tropospheric temperature and sea level pressure at Darwin*

The mean sea-level pressure (SLP) at Darwin is one of the important parameters used to represent ENSO variability, which has also been found to be more strongly associated with the monsoon rainfall variability (Elliot and Angell, 1988; Krishna Kumar *et al*. 1995) than with the other types of indices of ENSO.

The correlations between the detrended series of Darwin SLP and the all-India mean seasonal/annual temperatures at the surface and different tropospheric levels are presented in Table 5. A conspicuous feature of the correlations is the significant and negative simultaneous correlation between sea level pressure (SLP) at Darwin in MAM and tropospheric temperatures (surface to 200 hPa) during pre-monsoon season over India, whereas there is significant positive correlation between MAM SLP pressure at Darwin and the subsequent monsoon temperatures at surface and 850 hPa. It is interesting to note that there is strong negative simultaneous correlation between tropospheric temperatures from surface to 200 hPa and Darwin SLP pressure during MAM season. This simultaneous negative correlation persists through all the subsequent seasons up to SON. In this connection, it may be noted that sea level pressure during MAM at Darwin is significantly and positively correlated with that during the subsequent seasons JJA and SON, the CCs being 0.48 and 0.58 respectively. Therefore, part of the seasonal

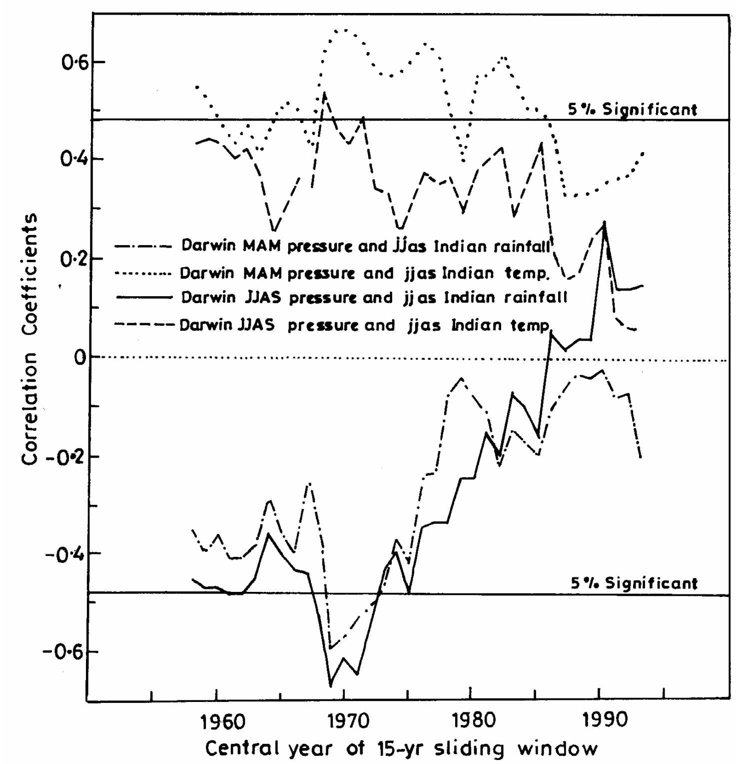


Fig. 9. 15- years sliding correlation of Darwin sea level pressure during MAM and JJA with Indian rainfall/ temperature during the monsoon season

persistence in the correlations between Darwin MAM pressure and Indian tropospheric temperature may be due to the seasonal persistence in Darwin pressure itself.

The secular variation in the relationship between Darwin pressure during MAM and JJA seasons and the Indian monsoon rainfall as well as monsoon temperature has been examined by means of 15-year sliding correlations, using the data for the period 1951-2000 (Fig. 9). The sliding correlations clearly indicate that the relationship between Darwin MAM pressure and the Indian surface temperature during monsoon season is positive over the entire period, and is also significant except in the beginning and end of the data period. The positive relationship is also observed with Darwin JJA pressure and Indian monsoon temperature at surface, however, the CCs are generally non significant. There is a slight indication that the relationship is weakened in the recent period (1985 onwards). The relationship of MAM and JJA pressure at Darwin with Indian rainfall is predominantly negative from beginning of the data period to the data period centered around 1975, after this period relationship rapidly weakens. Recently Krishna Kumar *et al*. (1999) have shown a weakening relationship between Indian monsoon and ENSO during the recent period. This feature is also reflected in the relationship of Darwin JJA pressure with the Indian surface temperature in both MAM and JJAS seasons (Fig. 9), but not as prominently as in the case of rainfall.

8. Conclusions

(*i*) The mean annual temperature shows warming of 0.18° C and 0.30° C per 10 years at the surface and 850 hPa levels respectively.

(*ii*) The surface temperatures show dominant warming trend during winter and monsoon seasons. The monsoon season is marked by considerable warming, the significant trends extending from the surface up to 700 hPa.

(*iii*) From 850 to 150 hPa, the standardized composite anomalies of pre-monsoon temperatures during excess (deficient) monsoon years are positive (negative), whereas at surface, they are marginally negative during excess as well as deficient monsoon years. However, on a monthly scale, the standardized temperature anomaly is considerably positive in the month of May for excess years, in contrast to the negative composite for deficient years, indicating that the tropospheric temperatures in the month of May have a predominant influence on the monsoon rainfall.

(*iv*) Tropospheric temperature anomaly composites as well as correlations of El-Nino years are negative for 3 seasons before the monsoon season and positive after the monsoon seasons, from surface to 500 hPa.

(*v*) The pre-monsoon pressure at Darwin is positively and significantly correlated with the subsequent monsoon season temperature over India, at the surface and 850 hPa levels.

(*vi*) Positive relationship is observed with Darwin MAM and JJA pressures and the Indian monsoon temperature at surface, with the CCs being statistically significant in the case of Darwin MAM pressures. There is some indication that this relation is weakened in recent period (1985 onwards), but not as prominently as in rainfall brought out by recent studies.

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