MAUSAM, **61**, 4 (October 2010), 455-468

551.576.2

Changes in total cloud cover over India based upon 1961-2007 surface observations

A. K. JASWAL

India Meteorological Department, Pune - 411 005, India

(*Received 22 September 2009, Modified 16 February 2010*)

e mail: akjaswal@imdpune.gov.in

सार – इस शोध पत्र में भारत के 172 सुवितरित सतह मौसम स्टेशनों में 1961 से 2007 तक की अवधि के दौरान मेघ आच्छादन में वार्षिक और मौसमी प्रवत्तियों और संबंद्ध जलवायविक परिवर्तनशीलता, दैनिक तापमान की रेंज और वर्षा वाले दिनों की जाँच की गई हैं। इन आँकड़ों के विश्लेषण से भारत के अधिकांश भागों में शीत ऋतु, ग्रीष्म ऋतु और मानसून वर्षा ऋतु के दौरान मेघ के कुल आच्छादन में सामान्य कमी का पता चलता है। मासिक पैमाने के आँकड़ों के आधार पर अप्रैल (3 प्रतिशत प्रतिदशक), जून से सितम्बर (2 प्रतिशत प्रतिदशक) और दिसम्बर (5 प्रतिशत प्रतिदशक) के दौरान मेघ के कुल आच्छादन में विशेष रूप से कमी आई है। ग्रीष्म ऋतु और मानसून ऋतु (2 प्रतिशत प्रतिदशक) में मेघ के कुल आच्छादन में मौसमी रूप से कमी की प्रवृत्तियाँ पाई गई हैं। इन प्रवृत्तियाँ के स्थानिक विश्लेषण से मध्य भारत (सभी ऋतुओं में) और दक्षिणी प्रायद्वीप (मानसूनोत्तर काल को छोड़कर) में मेघ के कुल आच्छादन में सुसंगत कमी का पता चलता है।

संपूर्ण भारत के दैनिक तापमान रेंज और वर्षा वाले दिनों में औसत मासिक और मौसमी प्रवृत्तियाँ मिली जुली और कमज़ोर हैं। स्थानकि तौर पर उत्तर में दैनिक तापमान रेंज में प्रवत्तियों में कमी आ रही है और दक्षिणी प्रायद्वीप में बढ़ोतरी हो रही हैं जबकि वर्षा वाले दिनों में प्रवत्तियाँ शीत ऋतु और मानसून ऋतु के दौरान अधिकांश स्टेशनों पर कम हो रही है और ग्रीष्म ऋतु और मानसून के बाद की ऋतु में बढ़ोतरी हो रही है। तथापि समान प्रवत्तियों वाले क्षेत्रों में प्रवत्तियों के आकार में मौसमों के बीच में काफी परिवर्तनशीलता पाई गई है। मानसून वर्षा ऋतु में मेघ के कुल आच्छादन और नीनों 3.4 समुद्र सतह तापमान की विसंगतियाँ उत्तर पूर्व क्षेत्रों को छोड़कर देश के सभी क्षेत्रों में विशेष रूप से नकारात्मक हैं जिनसे उनका मध्य प्रबल संबंध का पता चलता है।

ABSTRACT. Based upon 172 well distributed surface meteorological stations over India, annual and seasonal trends in total cloud cover and associated climatic variables diurnal temperature range and rainy days are investigated for 1961-2007. The data analysis indicates a general decrease in total cloud cover over most parts of India during winter, summer and monsoon. On monthly scale, statistically significant decrease in total cloud cover has occurred during April (3% per decade), June to September (2% per decade) and December (5% per decade). Seasonally, the declining trends in total cloud cover are significant for summer and monsoon (2% per decade). Spatial analysis of trends suggests coherent decrease in total cloud cover over central India (all seasons) and south peninsula (except post monsoon).

All India averaged monthly, annual and seasonal trends in diurnal temperature range and rainy days are mixed and weak. Spatially, trends in diurnal temperature range are decreasing over north and increasing over south peninsula while trends in rainy days are decreasing over large number of stations during winter and monsoon and increasing in summer and post monsoon seasons. However, the sizes of the same trend regions show considerable variability between seasons. Monsoon season total cloud cover and Nino3.4 sea surface temperature anomalies are significantly negatively correlated over all regions of the country except northeast indicating a strong relationship between them.

Key words – Total cloud cover, Diurnal temperature range, Rainy days, Trend, Aerosol, Nino3.4, Sea surface temperature, Correlation.

1. Introduction

Earth's climate has varied considerably over time and this variability is a response to various factors which include changes in solar insolation, increase in concentration of greenhouse gases and aerosols and large scale urbanization and deforestation. Such changes have the potential to influence earth's climate, though it is

TABLE 1

All India monthly, annual and seasonal means and trends of total cloud cover (TCC), diurnal temperature range (DTR) and number of rainy days (NRD) for the period 1961-2007 based upon 172 stations. Trend values in bold are significant at 95% level

	TCC		DTR		NRD	
	Mean (okta)	Trend (okta/decade)	Mean (°C)	Trend (°C/decade)	Mean (days)	Trend (days/decade)
January	2.0	no trend	13.6	- 0.09	0.9	- 0.03
February	1.9	-0.03	13.9	- 0.13	1.1	+ 0.04
March	2.0	-0.03	14.0	**- 0.10**	1.2	+ 0.02
April	2.6	**-0.08**	13.4	+ 0.01	1.8	+ 0.03
May	3.0	-0.02	12.3	- 0.07	3.1	+ 0.13
June	4.9	**-0.08**	9.8	- 0.03	7.9	+ 0.10
July	6.1	**-0.12**	7.5	no trend	12.3	- 0.25
August	6.0	**-0.12**	7.1	+ 0.05	11.9	- 0.26
September	4.8	**-0.08**	8.5	+ 0.03	8.2	- 0.15
October	3.1	-0.01	11.2	- 0.03	4.3	+ 0.04
November	2.4	-0.09	12.9	+ 0.01	2.1	- 0.02
December	2.2	**-0.12**	13.6	+ 0.09	1.1	- 0.10
Annual	3.4	**-0.07**	11.5	- 0.02	4.7	- 0.04
Winter	2.0	-0.05	13.7	- 0.04	1.0	- 0.03
Summer	2.5	**-0.05**	13.2	**- 0.05**	2.0	+ 0.06
Monsoon	5.5	**-0.10**	8.2	+ 0.01	10.1	- 0.15
Post monsoon	2.7	-0.05	12.1	- 0.01	3.2	+ 0.01

difficult to clearly delineate the characteristics of climate change associated with natural and anthropogenic forcings due to complex interactions within the climate system (IPCC 2001). Thus there is need of careful examination of meteorological data to reveal any signals in regional climate which may be useful to planners and government agencies.

Varying results for trends in cloud cover over different regions of the world were found by various authors. Some of the most noteworthy regional studies are by Henderson-Sellers (1992), Sun and Groisman (2000), Kaiser (2000), Groisman *et al*. (2004), Dai *et al*. (2006) and Warren *et al*. (2007). Based upon long period records of 350 stations worldwide, Henderson-Sellers (1992) found increases in cloud amounts over North America, Europe, India and Australia for 1900-1985. Sun and Groisman (2000) found that although total cloud cover increased in the former Soviet Union from 1936 to 1990, an opposite tendency was found for low cloud cover, which decreased significantly. Total cloud cover over United States has increased during 1976-2004 (Dai *et al*., 2006) along with increase in low cloud cover during last 50 years (Groisman *et al*., 2004). The most comprehensive study on trends in cloud cover was done by Warren *et al.* (2007) who utilized synoptic data from 5388 climate stations and found an average decrease in global mean cloud cover over land for the period 1971 to 1996. Kaiser (2000) has reported decreasing trends in total cloud cover over China. It is clear from these studies that historical trends in cloud cover are not uniform everywhere. There are very few published works about long term trends in total cloud cover over India. Rao *et al*. (2004) studied trends in annual total cloud amount over 15 stations in India and found decreasing trends at 11 stations. Regional studies done by Warren *et al.* (2007) have found decreasing trend in total cloud cover in India. Based upon 14 stations in southern India, Biggs *et al.* (2007) have reported decrease in annual total cloud amount by 0.09% per year during 1952-1997. Roy and Balling (2005) have found significant increase in cloud cover during summer over Jammu and Kashmir.

The main objective of this study is to present a more detailed and updated overview of the changes in total cloud cover experienced in India. As such, the spatial and

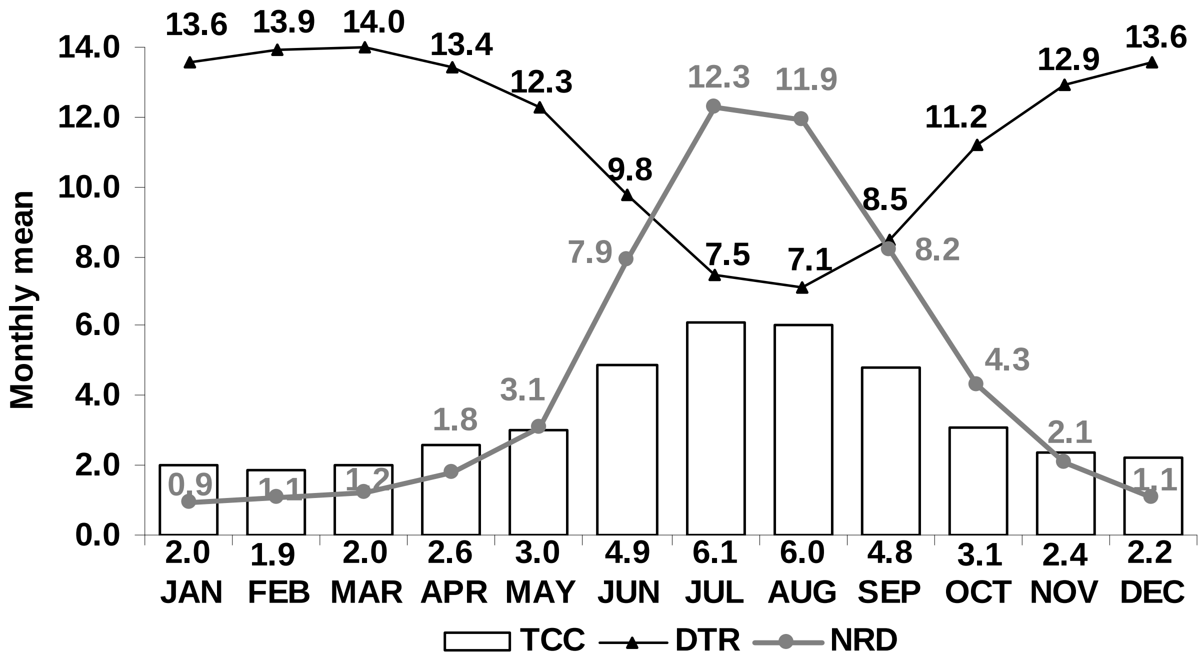


Fig. 1. All India mean total cloud cover (TCC) in okta, diurnal temperature range (DTR) in °C and number of rainy days (NRD) in days based upon 172 surface stations for 1961-2007

TABLE 2

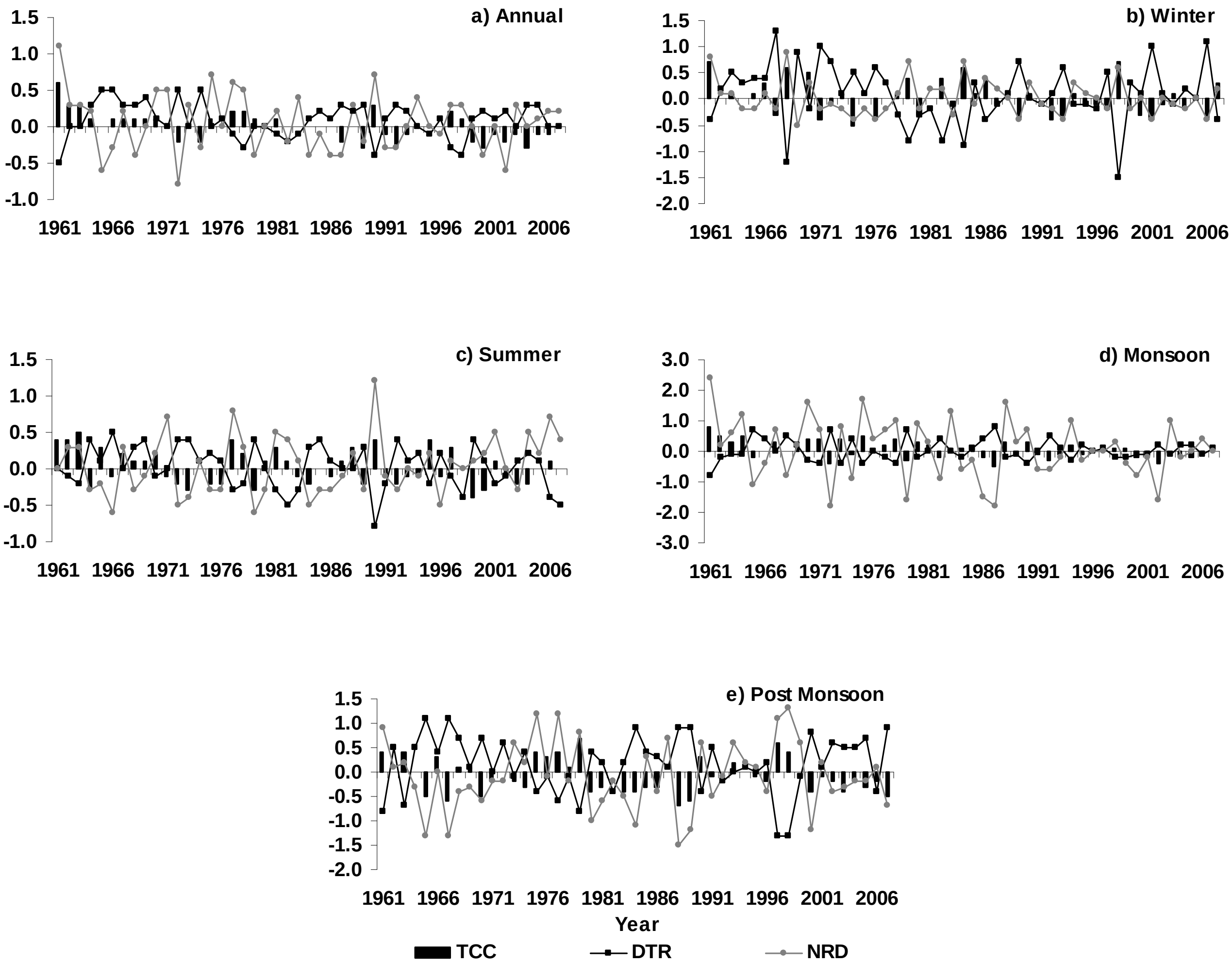
Numbers of stations (%) having increasing/decreasing trends in total cloud cover (TCC), diurnal temperature range (DTR) and number of rainy days (NRD) for annual, winter, summer, monsoon and post monsoon. Numbers in bold indicate stations (%) showing significant trends

	Type of Trend	Annual	Winter	Summer	Monsoon	Post monsoon
TCC	Increasing	36 (**13**)	36 (**13**)	40 (**17**)	29 (**9**)	44 (**13**)
	Decreasing	64 (**40**)	64 (**37**)	60 (**31**)	71 (**47**)	56 (**23**)
DTR	Increasing	46 (**29**)	47 (**26**)	48 (**24**)	52 (**24**)	46 (**16**)
	Decreasing	54 (**35**)	53 (**33**)	52 (**31**)	48 (**23**)	54 (**27**)
NRD	Increasing	31 (**2**)	32 (**3**)	59 (**13**)	21 (**2**)	58 (**2**)
	Decreasing	69 (**12**)	68 (**8**)	41 (**5**)	79 (**20**)	42 (**2**)

temporal variability of total cloud cover, diurnal temperature range and number of rainy days over the period 1961 to 2007 are investigated and discussed in section 3.

2. Data and methodology

A total number of 172 stations which have at least 90% cloud, temperature and rainy days data available for the period 1961 to 2007 were selected from the network of surface observatories of India Meteorological Department (IMD) and data for these stations were obtained from National Data Centre (NDC) located at Pune. Total cloud cover refers to the portion of the sky in eights (okta) covered by clouds at any height. In this study, observations recorded at 0300 and 1200 UTC were used for preparing mean total cloud cover. A rainy day is defined as a day when precipitation of 2.5 mm or more was measured while diurnal temperature range is the difference between the daily maximum and minimum temperatures. Annual and four seasons considered in the present work are annual (January to December), winter



Figs. 2(a-e). Temporal variations of total cloud cover (TCC) in okta, diurnal temperature range (DTR) in °C and number of rainy days (NRD) in days over India for 1961-2007. Data series are anomalies from 1971-2000 averages

TABLE 3

Number of stations (%) having negative correlation between total cloud cover (TCC) & diurnal temperature range (DTR) and positive correlation between total cloud cover (TCC) & number of rainy days (NRD) out of 172 stations under study for the period 1961-2007

	Number of stations (%)				
	Annual	Winter	Summer	Monsoon	Post monsoon
TCC and DTR (negative correlation)	82	93	86	90	92
TCC and NRD (positive correlation)	97	98	97	98	100

(December to February), summer (March to May), monsoon (June to September) and post monsoon (October to November).

The trends in mean total cloud cover (TCC), mean diurnal temperature range (DTR) and total number of rainy days (NRD) for 172 stations well distributed over India were calculated for 1961-2007. Linear trend analysis by the method of least square was used in this study and the trends were tested at 95% level of confidence using t-test. All India averaged monthly and seasonal trends in TCC, DTR and NRD are given in Table 1. India averaged monthly cycle of TCC, DTR and NRD is shown in Fig. 1. Annual and seasonal temporal variations of anomalies in TCC, DTR and NRD from 1971-2000 averages are shown in Figs. 2(a-e). Based upon 172 stations, annual and seasonal mean cloud patterns over India are shown in Figs. 3(a-e). Trends in TCC, DTR and NRD for annual and four seasons are shown in Figs. 4 (a-e) to 6 (a-e) where grey circles indicate decreasing trends and black circles indicate increasing trends. The statistically significant trends at 95% level of confidence are shown by an outer circle. Numbers of stations showing increasing/decreasing trends in TCC, DTR and NRD are given in Table 2 while numbers of stations having negative correlation between TCC & DTR and positive correlation between TCC & NRD are given in Table 3. For studying correlation between monsoon season TCC anomalies and Nino3.4 sea surface temperature (SST) anomalies, data for Nino3.4 (region in central Pacific bound between 120° - 170° W, 5° N - 5° S) was downloaded from website http://www. cgd.ucar.edu/. Spatial patterns of correlation between monsoon season Nino3.4 SST anomalies and the monsoon season TCC anomalies over India are shown in Fig. 7.

3. Results and discussion

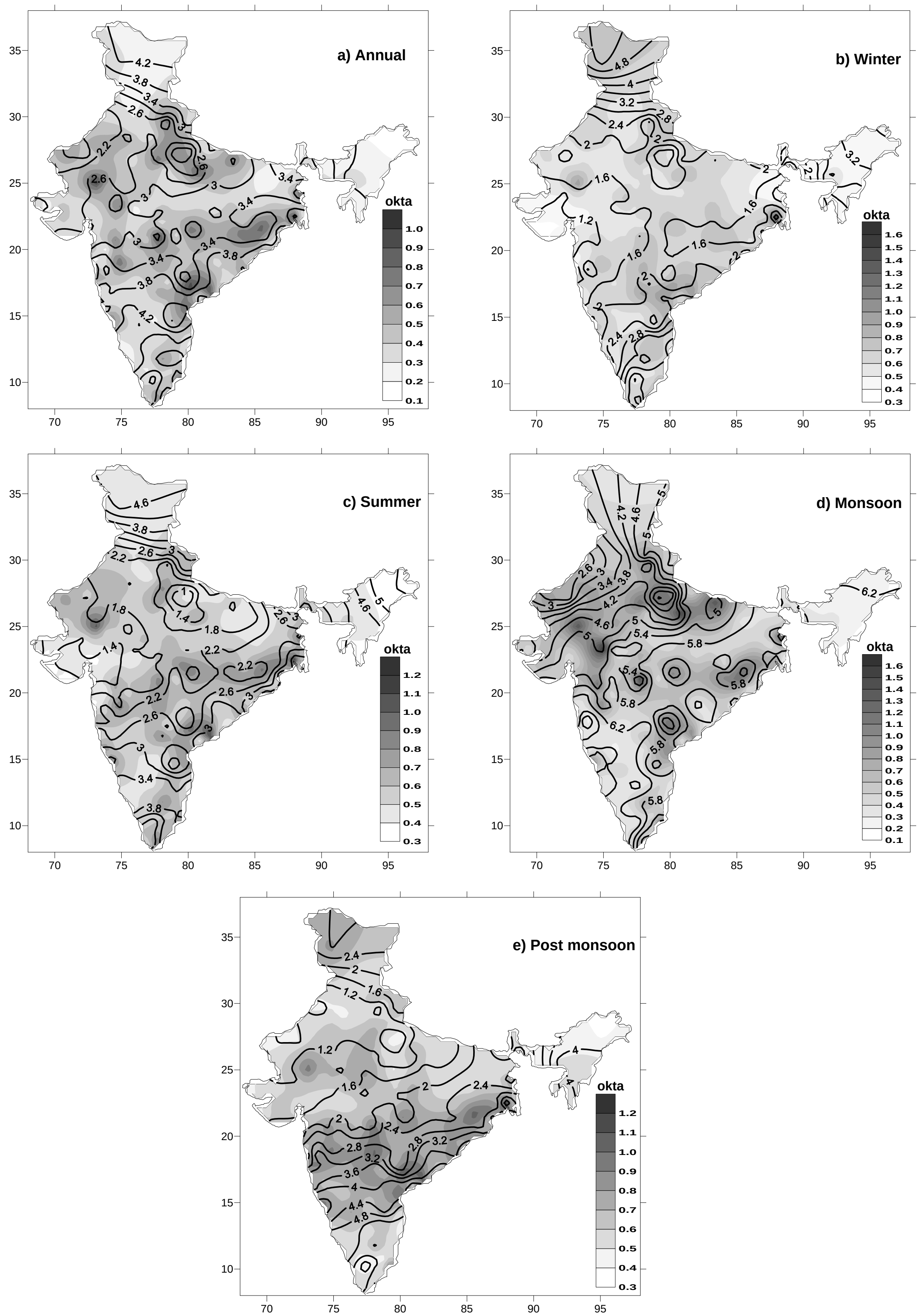
3.1. *All India averaged monthly, annual and seasonal means and trends*

Table 1 shows all India averaged monthly, annual and seasonal means and trends of TCC, DTR and NRD. Averaged monthly TCC over India is highest during monsoon months July and August (~6 okta) and least (~2 okta) during January to March. For country as a whole, monthly trends in TCC are decreasing for all months but are significant for April, June to September and December. Averaged monthly DTR is maximum (~14° C) during February to March and minimum during monsoon months July and August (~7° C). Monthly trends in DTR are decreasing for January to March, May to June and October out of which trend is significant for March only while trends are increasing (not significant) for April, August, September, November and December. Similar to TCC, averaged monthly mean NRD is maximum (~12 days) during monsoon months and minimum (~1 day) during winter months. Monthly NRD trends are decreasing (not significant) for January, July to September and November to December.

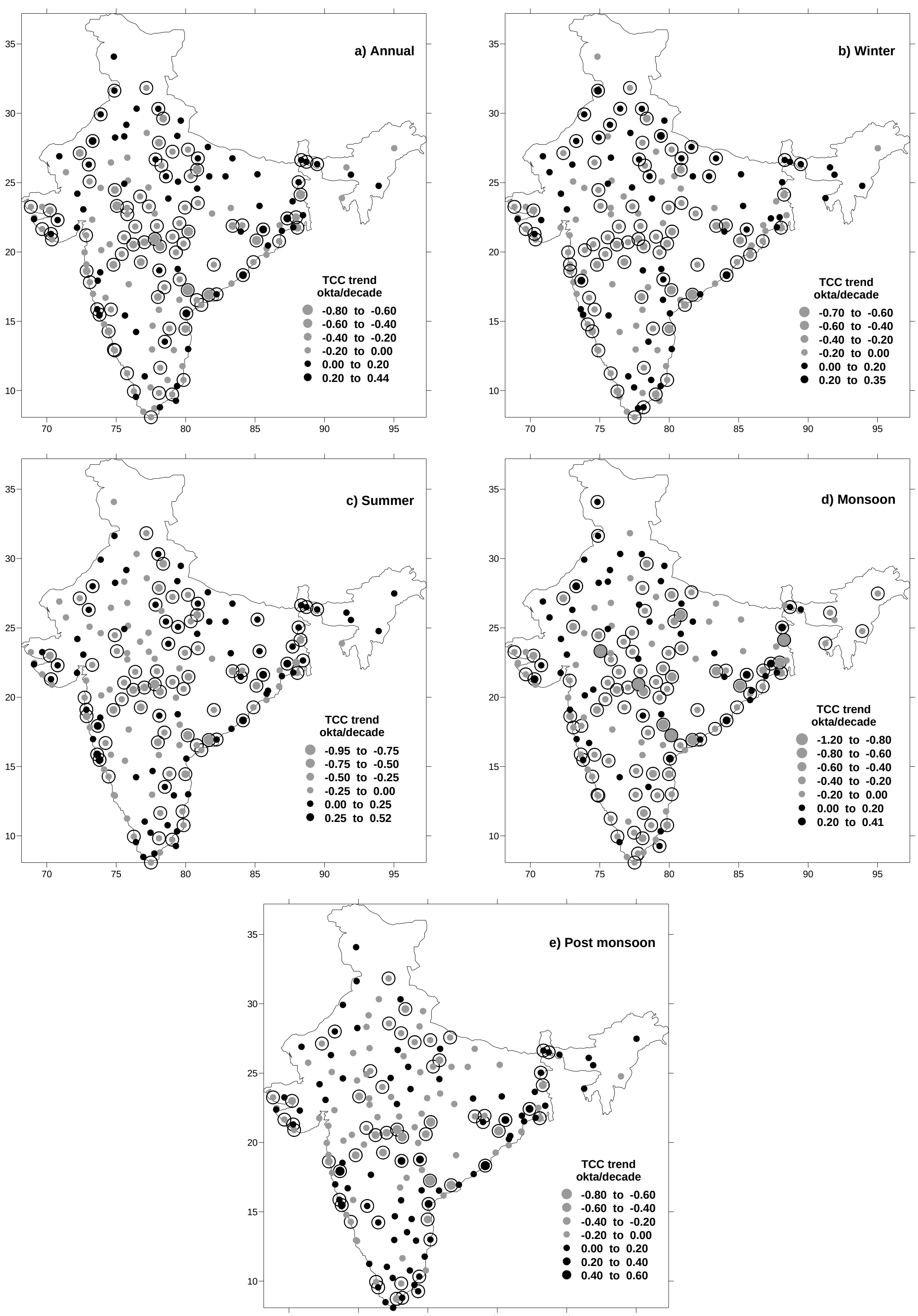
All India averaged annual mean TCC is 3.4 okta and the trend is decreasing significantly (-0.07 okta/decade). Annual mean DTR and NRD are 11.5° C and 4.7 days respectively with non significant decreasing trend. Seasonal mean TCC is highest (5.5 okta) in monsoon and lowest (2.0 okta) in winter while trends are decreasing for all seasons but significant for summer (-0.05 okta/decade) and monsoon (-0.1 okta/decade). Seasonal mean DTR is largest (13.7° C) in winter and smallest (8.2° C) in monsoon while trends are decreasing (significant for summer) except for monsoon season when it is increasing (not significant). NRD is highest in monsoon (10.1 days) and lowest in winter (1.0 days). All India averaged seasonal trends in NRD are not significant but trends are decreasing for winter and monsoon and increasing for summer and post monsoon seasons which is compatible with rainfall trends over India reported by Dash *et al*. (2007).

3.2. *Temporal variations*

Annual and seasonal temporal variations of TCC, DTR and NRD for 1961-2007 as anomalies from 1971-2000 average are shown in Figs. 2(a-e). It is clear from Fig. 2(a) that annual TCC and NRD anomalies are strongly positive and DTR anomaly strongly negative in 1961 which is one of the wettest years. Strong negative annual TCC anomalies are seen in 1972, 1974, 1987, 1989, 1992, 2000, 2002 and 2004 which have lower annual rainfall. TCC anomalies for winter season are highest (+0.7 okta) in 1961 and 1998 and lowest (-0.5 okta) in 1974 as shown in Fig. 2(b). Winter season NRD anomalies are highest (+0.9 days) in 1968 and lowest (-0.5 days) in 1967 while the highest DTR anomaly (+1.3° C) is in 1967 and lowest (-1.5° C) is in 1998. TCC time series for summer season is shown in Fig. 2(c) which indicate 1963 and 1999 as highest and lowest cloudy years respectively. The highest and lowest DTR anomalies for summer season are +0.5° C (1966) and -0.8° C (1990) respectively. Summer season NRD is highest (+1.2 days) in 1990 and lowest (-0.6 days) in 1966 and 1979. Monsoon season TCC and NRD anomalies are highest in 1961 which has the lowest DTR anomaly as shown in Fig. 2(d). Strong negative anomalies in TCC for monsoon season are obtained for drought years 1965 (-0.2 okta), 1972 (-0.4 okta), 1979 (-0.3 okta), 1987 (-0.5 okta), 1992 (-0.3 okta), 2002 (-0.4 okta) and 2004 (-0.2 okta) which also have simultaneous strong negative NRD and positive DTR anomalies. Post monsoon season TCC anomalies are



Figs. 3(a-e). Geographical distribution of mean total cloud cover (TCC) in okta over India for annual and four seasons based upon 172 stations for 1961-2007. Shaded regions in the background indicate variations in standard deviation of TCC



Figs. 4(a-e). Spatial distribution of trends in total cloud cover (TCC) in okta/decade for 1961-2007. Trends signifcant at 95% level are shown by an outer circle highest (+0.7 okta) in 1979 which have lower DTR (-0.8° C) and higher NRD (+0.8 days) anomalies [Fig. 2(e)]. The decreasing trends in DTR obtained during 1961 to 2007 are consistent with the global tendency as reported by Warren *et al*. (2007). The temporal variations indicate consistent lower TCC and NRD and higher DTR anomalies during last two decades.

3.3. *Cloud climatology - spatial distribution of mean total cloud cover*

Spatial distribution of TCC climatology over India based upon 1961-2007 is shown in Figs. 3(a-e). The patterns of annual mean TCC indicate region of highest clouding over north, northeast, Western Ghats and south peninsula [Fig. 3(a)]. The standard deviation is higher over Uttar Pradesh, west Madhya Pradesh, south Rajasthan and coastal Andhra Pradesh. The highest annual mean TCC is at Kodaikanal (5.7 okta) and lowest is at Mainpuri (1.4 okta). Distribution of winter season TCC [Fig. 3(b)] suggest region of higher cloud cover over north, northeast and southeast peninsula. Winter season mean TCC is highest at Srinagar (5.3 okta) and lowest at Berhampore (0.8 okta). Spatial patterns of summer mean TCC indicate regions of higher clouding over north, northeast and south peninsula as shown in Fig. 3(c). Summer season mean TCC is highest at Dibrugarh (5.4 okta) and lowest at Hardoi (0.7 okta). Fig. 3(d) shows distribution of mean monsoon TCC over India which is highest over northeast, Western Ghats and south peninsula. Monsoon season mean TCC is highest at Mahabaleshwar (7.6 okta) and lowest at Phalodi (2.4 okta). It is clear from Fig. 3(e) that regions over northeast and south peninsula are having highest post monsoon TCC.

3.4. *Spatial patterns of annual and seasonal trends in total cloud cover*

The spatial patterns of annual and seasonal trends in TCC over India are shown in Figs. 4(a-e) which indicate overall decline in total cloud cover over the country across all seasons but more coherently during winter and monsoon.

3.4.1. *Annual*

Out of 172 stations selected for study, 64% stations are exhibiting decrease in TCC as shown in Table 2. Annual TCC is decreasing significantly at 40% stations. Spatial distribution of annual trends in TCC indicates overall decrease in cloud cover over most parts of the country as shown in Fig. 4(a). The trend values range between -0.77 okta/decade and +0.41 okta/decade. Stations showing significant decreases are concentrated over central India, southeast and extreme south peninsula and along Indian coastline. Stations exhibiting significant increase in TCC are located in northwest and northeast India, west Rajasthan, east Uttar Pradesh, Bihar and West Bengal.

3.4.2. *Winter*

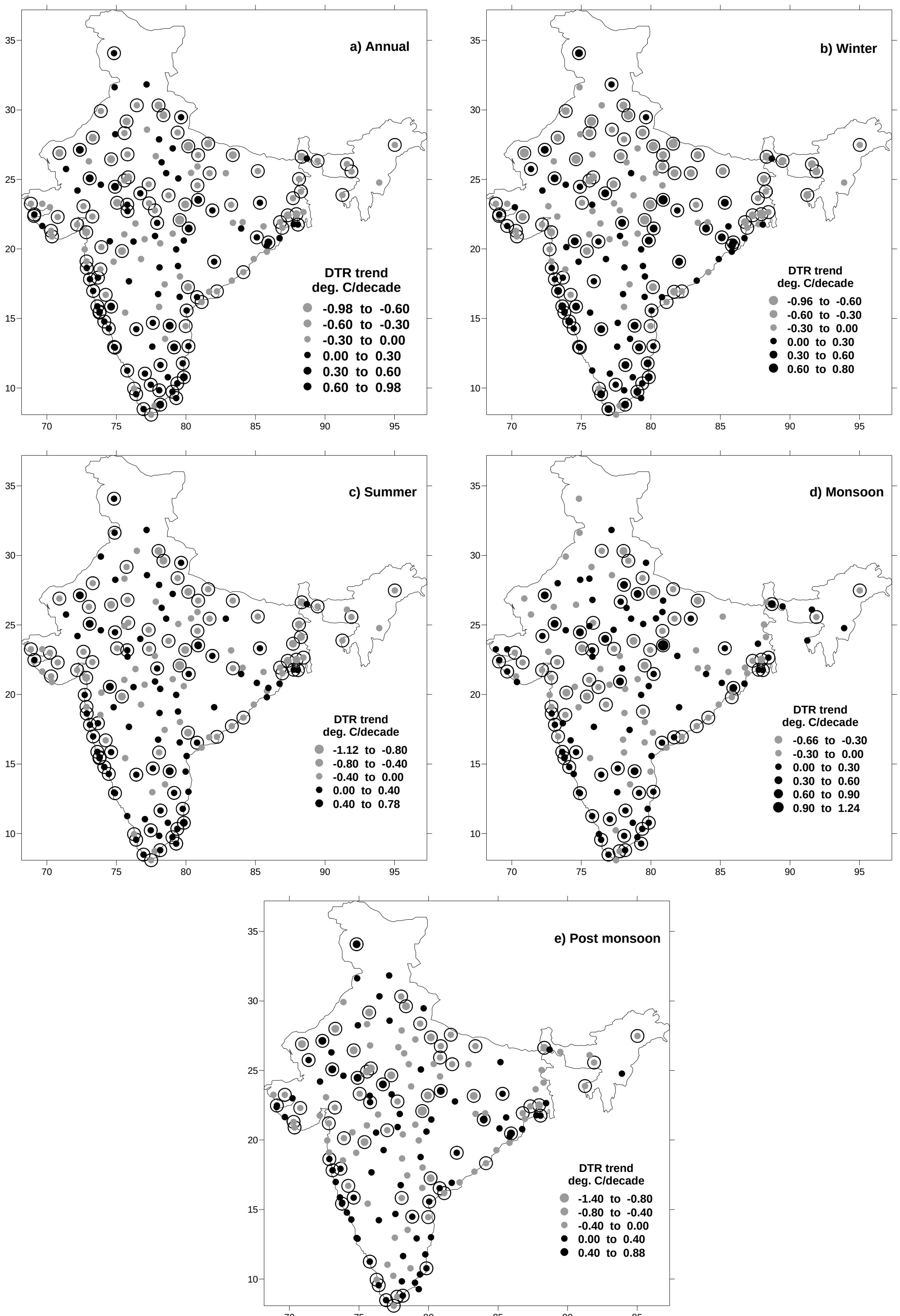
Similar to annual trends, winter TCC trends are decreasing at 64% stations as given in Table 2 and the spatial distribution of trends shows decline in cloud cover over large parts of the country. 37% stations are showing significant decrease and the trend values range between -0.68 okta/decade and +0.33 okta/decade. Stations showing significant decrease are more coherent over central India, southeast peninsula and along the Indian coastline. Trends are increasing over northwest India, east Uttar Pradesh, Bihar, West Bengal and northeastern states where stations with significant increases in TCC are located.

3.4.3. *Summer*

As given in Table 2, summer TCC trends are decreasing at 60% stations and decreasing significantly at 31% stations. The trend values range between -0.91 okta/decade and +0.51 okta/decade. Spatial distribution of trends suggests decrease over north, central and peninsular India [Fig. 4(c)]. Similar to annual and winter season, stations showing significant decrease are more coherent over central India and south peninsula. Coastal stations are also exhibiting decline in cloud cover. Trends are increasing over extreme northwest India, parts of Uttar Pradesh, Bihar, West Bengal and northeastern states. Stations having significant increase in TCC are more concentrated in Bihar and West Bengal. The trends over Jammu and Kashmir are decreasing contrary to results obtained by Roy and Balling (2005).

3.4.4. *Monsoon*

Out of 172 stations, 71% stations are exhibiting decrease and 47% stations are showing significant decrease in TCC which are highest for all periods considered. The spatial patterns of trends show decline over all regions of the country except for some pockets over north, northwest, east and west India as shown in Fig. 4(d). The decrease in cloud cover matches well with decrease in monsoon season rainfall noted by Dash *et al*. (2007). Significant increase in TCC is noticed over Jammu and Kashmir, north Rajasthan, West Bengal and south Gujarat. The trend values range between -1.16 okta/decade and +0.4 okta/decade. Stations showing significant decrease are more coherent over central and peninsular India and also along Indian coastline.



Figs. 5(a-e). Spatial distribution of trends in diurnal temperature range (DTR) in ºC/decade for 1961-2007. Trends signifcant at 95% level are shown by an outer circle

3.4.5. *Post monsoon*

Among seasonal TCC trends given in Table 2, post monsoon season have lowest numbers (56%) of stations exhibiting decreasing trend. 23% stations are showing significant decrease while 13% stations are showing significant increase in TCC. Spatial distribution of TCC trends suggests decrease over north and central India as shown in Fig. 4(e). The trend values range between -0.78 okta/decade and +0.53 okta/decade. Stations showing significant decrease are more clustered over Uttarakhand, western Uttar Pradesh and southern parts of central India. Trends are increasing over west Rajasthan, Bihar, West Bengal, northeastern states and south peninsula.

3.5. *Spatial distribution of trends in associated climatic variables*

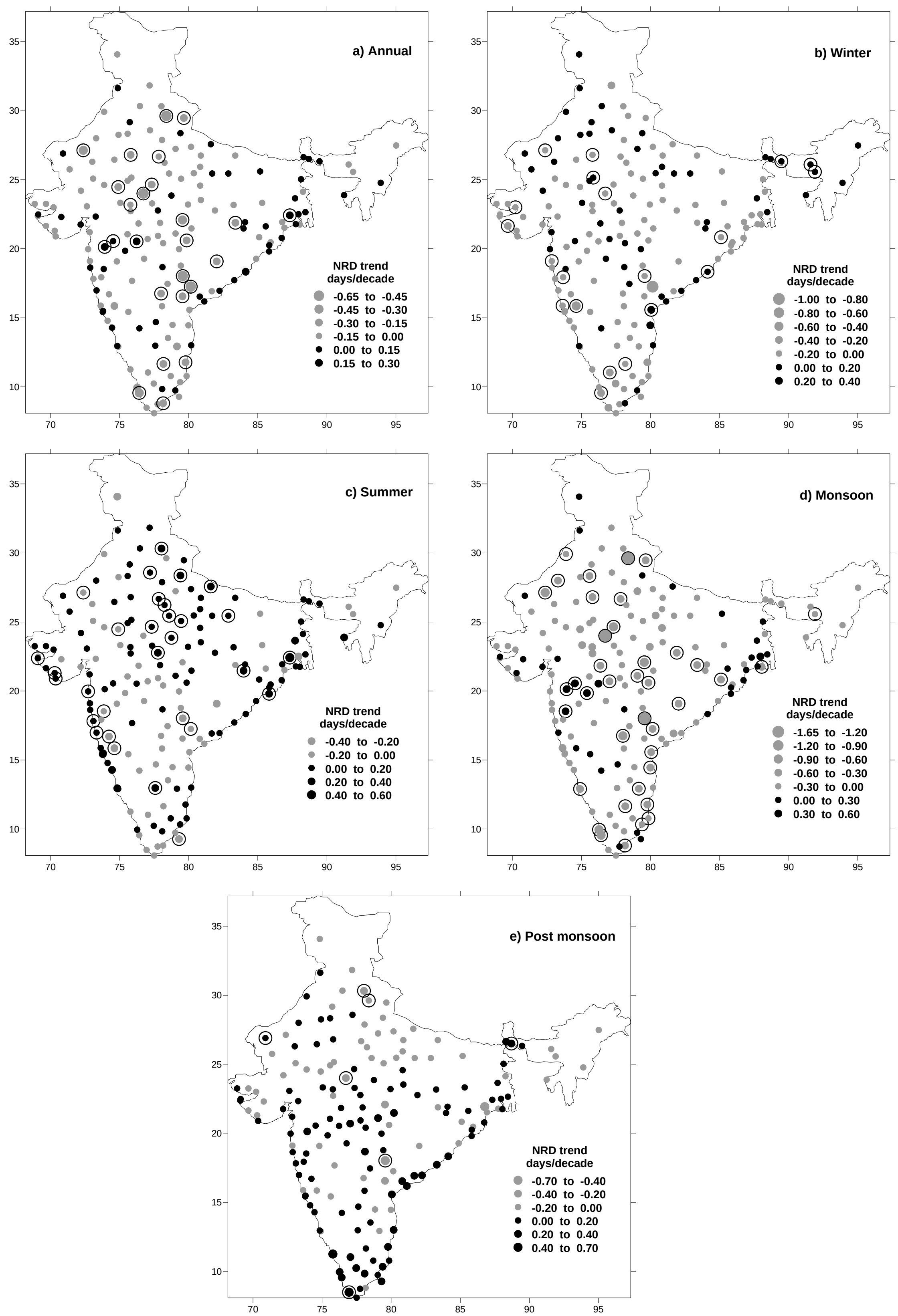
Clouds reduce the diurnal temperature range by shielding off solar radiation in daytime causing lower maximum temperatures and reradiating long-wave terrestrial radiation during night-time, avoiding the steep decline in surface temperature usually experienced during clear skies. Also, an increase in cloud cover, especially if it is low, will usually cause an increase in the number of rainy days and *vice versa*. Therefore, cloud amount values should usually have a negative relationship with DTR and a positive relationship with NRD (Dai *et al*., 1999).

3.5.1. *Trends in diurnal temperature range (DTR)*

It is clear from Table 2 that nearly 50% stations are showing decreasing trends in DTR for annual, winter, summer, monsoon and post monsoon out of which trends are significant at 35%, 33%, 31%, 23% and 27% stations respectively. Spatial distribution of trends in annual DTR indicates decrease over large parts of north, northeast, central and western India [Fig. 5(a)]. Most of the stations in these regions are exhibiting significant decrease. However, south peninsula is showing increase where most of the stations are having significant trends. The trend values range between -0.98° C / decade and +0.95° C / decade. Winter season spatial distribution of trends is almost similar to annual DTR patterns as shown in Fig. 5(b). However, it is interesting to note that stations in Jammu and Kashmir and Himachal Pradesh are showing significantly increasing trends in winter season DTR. Summer season DTR trend values are between -1.12°C/decade and +0.78°C/decade. The spatial patterns of trends suggest increase over Himachal Pradesh and Jammu & Kashmir, west coast and south peninsula [Fig. 5(c)]. Trends are significantly decreasing over large areas in Indo-Gangetic plains and northwest, northeast, central and east India. More numbers of stations are showing increase in monsoon season DTR trends as given in Table 2 and spatial distribution of trends indicates significant increase along west coast and extreme south peninsula [Fig. 5(d)]. However a few stations in Rajasthan, west Madhya Pradesh and Orissa also show significant increase in DTR. Stations in north, northeast and western parts of India have significant decrease in DTR. Spatial patterns of post monsoon season DTR trends [Fig. 5(e)] show significant decrease over Indo-Gangetic plains, northeast, north Maharashtra and Gujarat. Stations in Jammu and Kashmir, south Rajasthan, coastal Andhra Pradesh and extreme south peninsula are showing significant increase. DTR trends are increasing over south peninsula during winter, summer and monsoon seasons which do not agree with the trends reported by Roy and Balling (2005).

3.5.2. *Trends in number of rainy days (NRD)*

Table 2 shows that annual NRD trends are decreasing at 69% stations. Spatial distribution of annual NRD trends indicates overall decrease over India except over Bihar, West Bengal and north Maharashtra [Fig. 6(a)]. Stations showing significant decrease are more coherent over central and southeast peninsular India. Seasonally, winter (68%) and monsoon (79%) have higher numbers of stations exhibiting decreasing trends while summer and post monsoon seasons have higher numbers of stations with increasing trends (59% and 58% respectively). Spatial distribution of winter season trends indicates significant decrease in NRD over extreme south peninsula and along west coast of India [Fig. 6(b)]. Summer season NRD trends are increasing over north, central and east India while trends are decreasing over extreme north, northeast and peninsular India as shown in Fig. 6(c). 13% stations are having significant increase while 5% stations have significant decrease in summer season NRD. Most of the coastal stations are exhibiting increasing trends while stations in peninsular India are having decreasing trends. As is clear from Fig. 6(d), almost all regions of the country are showing decreasing trends in NRD for monsoon season except some pockets over north Maharashtra and West Bengal where trends are increasing. 20% stations are showing significant decrease which is more coherent over central India and southeast peninsula. The decreasing trends in NRD are compatible with decrease in monsoon cloudiness which may be due to increased concentration of small dust particles in the lower troposphere resulting in suppression of cloud formation leading to reduction in monsoon season rainfall over India as suggested by Rosenfeld (2000), Ramanathan *et al.* (2002) and Ghosh *et al.* (2005). Spatial patterns of post monsoon season NRD trends suggest increase over northwest, central, east and south peninsula. Regions over Jammu and Kashmir, Himachal Pradesh, Uttarakhand, east Uttar Pradesh, east Rajasthan, Gujarat and peninsular



Figs. 6(a-e). Spatial distribution of trends in number of rainy days (NRD) in days/decade for 1961-2007. Trends signifcant at 95% level are shown by an outer circle

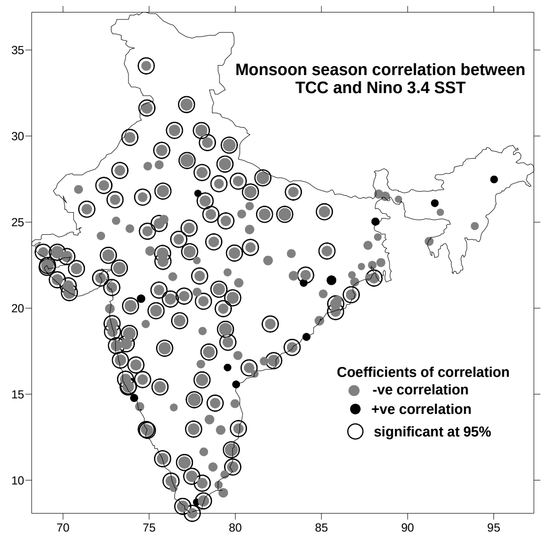


Fig. 7. Monsoon season correlation between total cloud cover (TCC) and Nino 3.4 sea surface temperature (SST) anomalies for 1961-2007. Stations showing significant correlation are marked by an outer circle

India is having decreasing trends in post monsoon season NRD. The increasing trends in summer and post monsoon season NRD suggest increase in convective rainfall over many regions of the country during these seasons.

3.6. *Correlation between monsoon season TCC and Nino 3.4 SST*

El Nino refers to the warm ocean waters in the central and eastern tropical Pacific which is one of the components of the El Nino-Southern Oscillation (ENSO) system. The inter-annual variability of the Indian monsoon is influenced, in a major way, by the El Nino and convection over the central Pacific called Nino 3.4 (120° - 170° W, 5°N - 5° S) and SST variations over this region are strongly correlated with the monsoon rainfall over India. One indication of this relationship is the significant correlation between monsoon season TCC and the Nino3.4 SST anomalies as shown in Fig. 7. Spatial patterns of coefficients of correlation (CC) between monsoon season TCC anomalies and Nino 3.4 SST anomalies indicate significant negative CCs over all regions of the country except northeast which are similar to patterns of correlation between ENSO index and total cloud cover anomalies reported by Warren *et al*. (2007). Parts of north, southwest and southeast India have more spatially consistent significant correlations. Stations showing significant CCs are more coherent over north, northwest and western parts of India where correlation values are about -0.6 at majority of stations. As the frequency of El-Nino events increased, a decrease in land cloud cover and increase in ocean cloud cover is reported by Warren *et al.* (2007). The significant negative correlation between the monsoon season total cloud cover over India and Nino3.4 SST anomalies as shown in Fig. 7 suggest strong relationship between ENSO and Indian monsoon system.

Annual and seasonal trends in total cloud cover and associated climate variables diurnal temperature range and rainy days are investigated for 1961-2007 in this paper. For country as a whole, statistically significant decrease in TCC has occurred during April (3% per decade), June to September (2% per decade) and December (5% per decade). The TCC trends obtained for India are similar to global trends reported by Dai *et al*. (2006) and Warren *et al.* (2007) and trends for China reported by Kaiser (2000) and Qian *et al*. (2006). DTR has significantly decreased in March only while trends in NRD are both increasing and decreasing (not significant). Seasonally, the strongest and most consistent evidence for decreasing cloud amount is seen for monsoon season where decreases ranging -0.08 to -0.12 okta per decade are observed over large parts of the country. Spatial patterns of trends in TCC suggest significant decreases (-0.2 okta/per decade) at most of the stations in north, central and peninsular India. The simultaneous study of associated variables suggest similar patterns of trends in number of rainy days but DTR trends over the country have both geographical and seasonal preferences. Increase in DTR at coastal stations show consistency with decrease in TCC suggesting major role of daily cloud amount in the increase of DTR.

For the vast majority of stations utilized in this study, there are negative linear correlations between TCC and DTR and positive correlation between TCC and NRD as given in Table 3 which provides additional confidence in the data. Therefore, it can be expected that if there are areas with significant trends in TCC, essentially the same areas should show significant trends in DTR (opposite sign) and NRD (same sign). The comparison of patterns of trends in TCC (Fig. 4) and DTR (Fig. 5) are quite interesting as regions of significant decrease in TCC over west coast and south peninsula have identifiable regions of increase in DTR for all seasons (except post monsoon). For the central India, however, where for all seasons an area of significant decrease in TCC is seen, an area with clear increase in DTR is missing which suggest the role of other factors in explaining the obtained trends. Winter season significant increase in TCC over Indo-Gangetic plains are accompanied by significant decrease in DTR over the region is very much evident. A recent study by Venkataraman *et al*. (2005) has shown that seasonal biomass-burning smoke and dust storms are the major sources of black carbon and aerosols in the Indo-Gangetic plains which along with the low topography of the Indo-Gangetic plains adjacent to the Himalayan ranges leads to formation of low clouds and dense fogs during the winter season. Also, the number of foggy days during winter season has been increasing in recent years as compared to earlier decades (De *et al*., 2001) with strong increasing trends of anthropogenic pollution in the Indo-Gangetic plains as reported by Sarkar *et al*., 2006.

Figs. 6(a-e) shows the seasonal tendencies in the number of rainy days and a causal relationship between increased (decreased) cloud cover and increased (decreased) number of rainy days can be inferred. The spatial analysis of trends in TCC and NRD over the country agrees in sign but differs in magnitude for all periods except over central India (post monsoon). As can be seen from Table 2, lesser numbers of stations show significant trends in NRD in comparison to trends in TCC. For post monsoon season, while trends in TCC over central India are significantly decreasing, trends in NRD are increasing though not significantly. Significant decrease in TCC along with significant decrease in NRD at large number of stations during monsoon season is noteworthy which agrees with trends in monsoon rainfall noted by Dash *et al.* (2007). Although aerosols suppress precipitation, the entire cloud-aerosol interaction enhances the formation of deeper clouds leading to heavy convective rainfall which is seen quite frequently in recent decade over Himalayas and Western Ghats (Dash and Hunt 2007). These decreasing trends in cloud cover are especially interesting in light of recent temperature trends observed over India by Roy and Balling (2005), Kothawale and Rupa Kumar (2005) and Dash *et al.* (2007) who have found increase in maximum and minimum temperature over the country. Clouds are expected to play a role in DTR change because of their unbalanced effects on maximum and minimum temperatures. Reductions of DTR over the past few decades have been documented in many regions of the world and increase in cloud cover and aerosols have been suggested as main contributors (Karl, *et al*. 1995; Dai, *et al*. 1999).

The interactions between aerosols and clouds have large uncertainties associated with climate forcing (IPCC 2001) and their interactions cause reduction in cloud droplet size, thereby an increase in cloud albedo and suppression in precipitation. Krüger and Grassl (2004) have given evidence of absorbing aerosols causing reductions in low-level and middle-level cloud cover over southeast China. However, there is another mechanism that suggests reduction in cloud cover due to aerosols (soot) which is responsible for offsetting the radiative cooling at the top of the atmosphere (Ackerman, *et al*., 2000). Emissions of aerosol precursors in South Asia have increased about six fold since 1930 (Ramanathan, *et al.* 2005) and atmospheric visual range has correspondingly decreased (De, *et al*. 2001 and Kaiser and Qian 2002). The model of Ramanathan, *et al*. (2005) simulated the 'indirect effects' of aerosols including cloud inhibition, but found no change in cloud cover over India.

4. Conclusions

The data analysis presented in this paper clearly indicates decrease in total cloud cover over large parts of India during 1961-2007. While trends in rainy days are similar to cloud cover across periods, trends in diurnal temperature have regional to seasonal preferences over the country. The results of this study are summarized as follows:

(*i*) In general, there has been a decrease in mean total cloud cover over most parts of India, but more strongly during the last two decades. The data analysis indicates decrease over many parts of the country during winter, summer and monsoon where significant decline at 37%, 31% and 47% stations respectively is found.

(*ii*) All India averaged monthly trends in total cloud cover show statistically significant decrease during April (3% per decade), June to September (2% per decade) and December (5% per decade). However, the declining trends are significant for summer and monsoon (2% per decade) only. Averaged monthly, annual and seasonal trends in diurnal temperature range and rainy days are mixed and weak.

(*iii*) Spatially, trends in total cloud cover and rainy days are more coherent over central India (for all seasons) and south peninsula (except post monsoon). Trends in diurnal temperature range are decreasing over north and increasing over south peninsula but the sizes of the same trend regions show considerable variability between seasons.

(*iv*) Monsoon season total cloud cover and Nino3.4 sea surface temperature anomalies are showing significantly negative correlation over all regions of the country except northeast which suggests a strong relationship but not a factor in overall decline in cloud cover. Regions of significant negative correlations are more coherent over north, northwest and western parts of India.

In addition to aerosol inhibition of cloud formation, several other processes may be contributing to the changes in cloudiness over India. With increased global warming, it will be important to examine variations in individual cloud types in future studies.

Acknowledgements

The author is grateful to referee(s) for constructive suggestions and review of the manuscripts.

References

Ackerman, A. S., Toon, O. B., Stevens, D. E., Heymsfield, A. J., Ramanathan, V. and Welton, E. J., 2000, "Reduction of tropical cloudiness by soot", *Science*, **288**, 1042-1047.

Biggs, T. W., Scott, C. A., Rajagopalan, B. and Turral, H. N., 2007, "Trends in solar radiation due to clouds and aerosols, southern India, 1952-1997*", Int. J. Climatol*., **27**, 1505-1518.

Dai, A., Trenberth, K. E. and Karl, T. R., 1999, "Effects of clouds, soil moisture, precipitation, and water vapor on diurnal temperature range", *J. Clim*., **12**, 2451-2473.

Dai, A., Karl, T. R, Sun, B. E. and Trenberth, K. E., 2006, "Recent trends in cloudiness over the United States: A tale of monitoring inadequacies", *Bull. Amer. Meteor. Soc*., **87**, 597-606.

Dash, S. K. and Hunt, J. C. R., 2007, "Variability of climate change in India", *Curr. Sci*., **93**, 6, 782-788.

Dash, S. K., Jenamani, S. R. and Panda, S. K., 2007, "Some evidence of climate change in twentieth-century India", *Climatic change*, **85**, 299-321.

De, U. S., Rao, G. S. P. and Jaswal, A. K., 2001, "Visibility over Indian airports during winter season", *Mausam*, **52**, 4, 717-726.

Ghosh, S., Davila, J., Hunt, J. C. R., Srdic, A., Fernando, H. J. S. and Jonas, P. R., 2005, "How turbulence enhances coalescence of settling particles with applications to rain in clouds", Proc. R. Soc., London, A, **461**, 3059-3088.

Groisman, P. Y., Knight, R. W., Karl, T. R., Easterling, D. R., Sun, B. and Lawrimore, J. H., 2004, "Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations", *J. Hydromet*., **5**, 64-85.

Henderson-Sellers, A., 1992, "Continental cloudiness changes this century", *Geo. J*., **27**, 255-262.

IPCC, 2001, "Climate Change 2001: The scientific basis", Cambridge University Press, Cambridge, U.K.

Kaiser, D. P., 2000, "Decreasing cloudiness over China: An updated analysis examining additional variables", *Geophys. Res. Lett*., **27**, 15, 2193-2196.

Kaiser, D. P. and Qian, Y., 2002, "Decreasing trends in sunshine duration over China for 1954–1998: Indication of increased haze pollution?", *Geophys. Res. Lett*., **29**, 21, 20-42.

Karl, T. R., Knight, R. W. and Plummer, N., 1995, "Trends in high-frequency climate variability in the twentieth century", *Nature*, **377**, 217-220.

Kothawale, D. R. and Rupa Kumar, K., 2005, "On the recent changes in surface temperature trends over India", *Geophys. Res. Lett*., **32**, L18714.

Krüger, O., and Grassl, H., 2004, "Albedo reduction by absorbing aerosols over China", *Geophys. Res. Lett*., **31,** L02108, doi:10.1029/2003GL019111.

Qian, Y., Kaiser, D. P., Leung, L. R. and Xu, M., 2006, "More frequent cloud-free sky and less surface solar radiation in China from 1955 to 2000", *Geophys. Res. Lett*., **33,** L01812, doi:10.1029/2005GL024586.

Ramanathan, V., Crutzen, P. J., Mitra, A. P. and Sikka, D. R., 2002, "The Indian Ocean experiment and the Asian Brown Cloud", *Curr. Sci*., **83**, 947-955.

Ramanathan, V., Chung, C., Kim, D., Bettege, T., Buja, L., Kiehl, J. T., Washington, W. M., Fu, Q., Sikka, D. R. and Wild, M., 2005, "Atmospheric brown clouds: impacts on South Asian climate and hydrological cycle", Proceedings of the National Academy of Sciences, **102**, 15, 5326-5333.

Rao, G. S. P., Jaswal, A. K. and Kumar, M. S., 2004, "Effects of urbanization on meteorological parameters", *Mausam*, **55**, 3, 429-440.

Rosenfeld, D., 2000, "Suppression of rain and snow by urban and industrial air pollution", *Science*, **287**, 1793-1796.

Roy, S. S., and Balling Jr., R. C., 2005, "Analysis of trends in maximum and minimum temperature, diurnal temperature range, and cloud cover over India", *Geophys. Res. Lett*., **32**, L12702, doi:10.1029/2004GL022201.

Sarkar, S., Chokngamwong, R., Cervone, G., Singh, R. P. and Kafatos, M., 2006, "Variability of aerosol optical depth and aerosol forcing over India", *Adv. Space Res*., **37**, 12, 2153-2159.

Sun, B. and Groisman, P. Ya., 2000, "Cloudiness variations over the former Soviet Union", *Int. J. Climatol*., **20** 1097-1111.

Venkataraman, C., Habib, G., Eiguren-Fernandez, A., Miguel, A. H. and Friedlander, S. K., 2005, "Residential biofuels in south Asia: Carbonaceous aerosol emissions and climate impacts", *Science*, **307**, 1454-1456.

Warren, S. G., Eastman, R. M. and Hahn, C. J., 2007, "A survey of changes in cloud cover and cloud types over land from surface observations, 1971-1996", *J. Clim*., **20** 717-738.