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Variability and trends in low cloud cover over India during 1961-2010

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सार – 1961-2010 की समयावधि में भारत के ऊपर निचले स्तर के मेघ आवरण में वार्षिक और ऋतुनिष्ठ परिवर्तनशीलता और प्रवृत्ति का विश्लेषण किया गया है। इस पूरी समयावधि में भारत के अधिकांश क्षेत्रों के ऊपर माध्य निचले मेघ आवरण में सामान्यत: कमी पाई गई है। किंतु भारतीय गांगेय मैदानों और पूर्वोत्तर भारत में वृद्धि देखी गई है। भारत पर दीर्घ अवधि माध्य निचले मेघों में मॉनसून के समय सबसे ऊँचे मेघ आवरण 39.4%) और शीतकाल में सबसे निचले मेघ आवरण (10.5%) के साथ अंत: वार्षिक परिवर्तनशीलता रही। वार्षिक माध्य निचले स्तर के मेघ आवरण प्रति दशक – 0.45% की कमी की प्रवृत्ति को दर्शाते हैं जो कि मुख्यरूप से मॉनसून की वजह से है जब कमी का दर प्रतिदशक – 1.22% है। मध्य भारत में घटने वाली बड़ी प्रवृत्तियों के परिमाण के साथ कुल स्टेशनों की संख्या में से क्रमश: वार्षिक, शीतकाल, ग्रीष्मकाल, मॉनसून काल और मॉनसूनोत्तर में 65%, 47%, 53%, 71% और 37% स्टेशनों में कमी की प्रवृत्ति देखी गई है। निचले मेघ आवरण में ऋतुनिष्ठ पैटर्न की प्रवृत्तियां स्थानिक रूप से अधिकांश मामलों में वार्षिक प्रवृत्तियों की पुष्टि करती हैं। आँकड़ों के विश्लेषण करने से यह पता चलता है कि शोध पत्र में किए गए अध्ययन के दौरान निचले मेघ आवरण का अधिकतम तापमान और दैनिक तापमान परास के साथ प्रबल नकारात्मक सहसंबंध और बारिश वाले दिनों के साथ प्रबल सकारात्मक सहसंबध है।

ABSTRACT. Annual and seasonal variability and trends in low cloud cover over India were analyzed for the period 1961-2010. Taking all period into account, there is a general decrease in mean low cloud cover over most regions of India, but an increase in the Indo-Gangetic plains and northeast India. Long term mean low cloud cover over India has inter-annual variations with highest cloud cover (39.4%) in monsoon and lowest cloud cover (10.5%) in winter season. The annual mean low cloud cover shows significant decreasing trend of -0.45% per decade, mainly contributed by monsoon where declining rate is -1.22% per decade. Out of the total numbers of stations showing decreasing trends, 65%, 47%, 53%, 71% and 37% of the stations show significant decrease in low cloud cover for annual, winter, summer, monsoon and post monsoon respectively, with large trend magnitudes occurring in central India. Spatially, the seasonal patterns of trends in low cloud cover confirm the annual patterns in most cases. Data analyses show that low cloud cover is having a strong negative correlation with maximum temperature and diurnal temperature range and a strong positive correlation with numbers of rainy days during the period of study.

Key words – Low cloud cover, Maximum temperature, Diurnal temperature range, Rainy days, Trends, Correlation.

1. Introduction

Cloudiness or cloud cover is a meteorological parameter important not only for weather forecasting but also for climatology. The importance of the spatial extent of cloudiness in the study of climate variability was shown by Zhang and Ramanathan (1999). Clouds have an enormous impact on weather and climate by reflecting sunlight, blocking outgoing longwave radiation and producing precipitation on planet Earth. In fact, clouds also play an important role in the recycling of water vapour from the Earth's surface to the atmosphere and back again. Clouds are the main cause of interannual and decadal variability of radiation reaching the Earth's surface and therefore they exert a dominant influence on the global energy balance. But cloud cover variability is one of the most uncertain aspects in climate model predictions (Wielicki *et al*., 1995; Bony and Dufresne, 2005; IPCC 2007; Sherwood *et al*., 2014). Cloudiness can contribute to cooling by low-level clouds (Mace *et al*., 2006) as well as to warming by the presence of high clouds (Lynch, 1996; Mace *et al*., 2006). Clouds cover about two thirds of the Earth's surface and exert great effects on Earth's radiation budget (Wild *et al*., 2004) and climate change by producing precipitation, reflecting shortwave solar radiation coming from the sun and returning outgoing longwave radiation from the surface (IPCC, 2007). The effect of clouds on the earth's radiation budget, the "cloud radiative forcing" is generally negative in the daytime but positive at night (Ramanathan *et al*., 1989; Harrison *et al*., 1990). Therefore, knowledge of variations in cloud cover may improve our comprehension of the role of clouds in contemporary climate change (Warren *et al*., 2007).

Some of the noteworthy regional studies of changes in cloud cover are by Henderson-Sellers (1992), Sun and Groisman (2000), Kaiser (2000), Sun and Groisman 2004; Groisman *et al*. (2004), Dai *et al*. (2006) and Warren *et al*. (2007). These studies have focused mostly on long-term trends, for Europe (Warren *et al*., 2007; Sanchez-Lorenzo *et al*., 2012), North America (Henderson-Sellers 1989; Milewska 2004; Warren *et al*., 2007), Australia (Jones and Henderson-Sellers 1992; Jovanovic *et al*., 2011), the United States (Sun 2003; Sun and Groisman 2004; Groisman *et al*., 2004; Dai *et al*., 2006) and the former Soviet Union (Sun and Groisman 2000; Sun *et al*., 2001). Analyses of cloudiness records suggest increased total cloud cover over the United States (Karl and Steurer 1990; Sun 2003; Groisman *et al*., 2004; Dai *et al*., 2006; Warren *et al*., 2007), Canada (Milewska, 2004), the former Soviet Union (Sun and Groisman 2000; Sun *et al*., 2001), Western Europe, mid-latitude Canada, Russia (Chernokulsky *et al*., 2011; Sanchez-Lorenzo *et al*., 2012) and Australia (Henderson-Sellers 1992; Jovanovic *et al*., 2011). In contrast, a decreasing trend in the total cloud cover has been revealed over much of China during 1951-1994 (Kaiser, 1998, 2000) and 1954-2005 (Xia, 2010), over the United States since the 1980s (Sun 2003; Sun and Groisman 2004), India during 1961-2007 (Jaswal 2010), most of South Africa during 1960-2005 (Kruger, 2007) and Italy during 1951-1996 (Maugeri *et al*., 2001). On the other hand, total cloud cover trends are also period specific over some regions. Several authors have found significant positive trends in U.S. total cloud for periods beginning in or after 1947 and ending before 1996 (e.g., Angell 1990; Plantico *et al*., 1990; Sun *et al*., 2001), but Elliott and Angell (1997) found no significant trend in cloudiness for 1973-93. Sun (2003) indicates increasing trends from about 1950 to 1990 but declining cloud cover from the 1980s to 2000, suggesting that the positive trend might be limited to the period from about 1950 to the 1980s. Sun and Groisman (2000) showed that in the former USSR low-level cloud cover has significantly decreased during the period 1936 to 1990. On continent scale, Warren *et al*. (2007) found a large decrease for South America, small decreases for Eurasia and Africa, and no trend for North America in total cloud cover during 1971-1996. Warren *et al*. (2007) has attributed decreasing trends in cloud cover on many continents and that some of these trends are linked to ENSO variations.

From the above-mentioned studies it is clear that historical trends in cloud cover are not uniform all over the globe but showing regional patterns. Even though there is large number of studies documenting total cloud cover, very few studies are available about changes in low cloud cover. This is first study about long term changes in low cloud over India. In this paper we have analyzed spatial and temporal changes in low cloud cover over India, which are derived from surface meteorological data (synoptic hours) for the period 1961-2010.

2. Data and methodology

Visual observations of cloudiness are important baseline datasets in climate studies. They have been used in analyses of climate change and meteorological processes, to evaluate cloud-climate interactions in climate models and to validate radiance-derived satellite cloud characteristics. Human observers report weather conditions in their area at a fixed time to produce a 'snapshot' of prevailing cloud condition.

2.1. *Method of observation*

Observations of cloud cover made at surface meteorological stations are recorded visually by trained observers in units of eighths of sky (okta) following the guidelines given by the World Meteorological Organization (WMO). The surface observations of clouds are made in the "synoptic" code which is exchanged globally through Global Telecommunication System (GTS). Clouds are classified as high, middle or low according to the altitude of the cloud base above the surface of earth. The information about clouds in the synoptic weather report consists of total cloud amount, individual cloud layer's cloud amount and cloud type (high, medium and low) and base height of the lowest layer of cloud. Low cloud amount recorded in the observations are the amount of sky estimated to be covered by low cloud types. The surface cloud observations have provided the long-term cloud climatologies (Warren *et al*., 1986 and 1988; Hahn and Warren, 1999), evaluation of satellite cloud observations (Rossow and Schiffer, 1999) and analyzing decadal and long-term changes in cloud cover during the last 100 years or so. Since weather reports of clouds are available for several decades with no change in official observing methods, long-term variations and trends in cloud cover can be studied.

2.2. *Data used*

We have selected 215 surface meteorological stations under network of India Meteorological Department for analyzing changes in low cloud cover over India. Geographical locations of these 215 stations with numbers of year data available during 1961-2010 are shown in Fig. 1. Low cloud amount, maximum temperature, minimum temperature and numbers of rainy days data for these 215 stations were taken from the archives of India Meteorological Department (IMD). For the entire study period the observation practice of cloud observation in IMD has remained consistent with World Meteorological Organisation (WMO) standards. Low cloud amount refers to the portion of the sky in eights (okta) covered by clouds at any height. Even though surface observations of low cloud amount are recorded at every synoptic hour, only daytime observations taken at main synoptic hours 0300 UTC and 1200 UTC are considered in this study. Here low cloud amount averaging is based on the daytime low cloud in order to avoid the surface nighttime cloud detection bias due to insufficient illumination (Hahn *et al*., 1995). The mean low cloud amount is converted in % by dividing cloud amount in okta by 8 and multiplying by 100. Additionally, low cloud cover (LCC) relationship with climate variables, mean maximum temperature (T_{MAX}), diurnal temperature range (DTR - the difference between the daily maximum and daily minimum temperature) and number of rain days (NRD) is also studied. A rainy day in IMD is defined as a day when total precipitation is 2.5 mm or more, as such number of rainy days in a month is count of such days. From monthly values, time series of mean annual (January-December), winter (December, January, February), summer (March-May), monsoon (June-September) and post monsoon (October-November) LCC, T_{MAX}, DTR and NRD were prepared for 1961-2010. All India averaged time series for annual and seasonal LCC, T_{MAX}, DTR and NRD were prepared by averaging all 215 stations.

Temporal variations in annual and seasonal all India averaged LCC is shown in Figs. 2(a-e). To describe the low cloud cover climatology, the mean and standard deviations of annual and seasonal LCC are presented in Fig. 3(a-e) where spatial patterns of mean LCC are shaded in color in the background and standard deviation from mean is shown as contour lines in the foreground. Long-term variability of cloudiness was estimated by using the

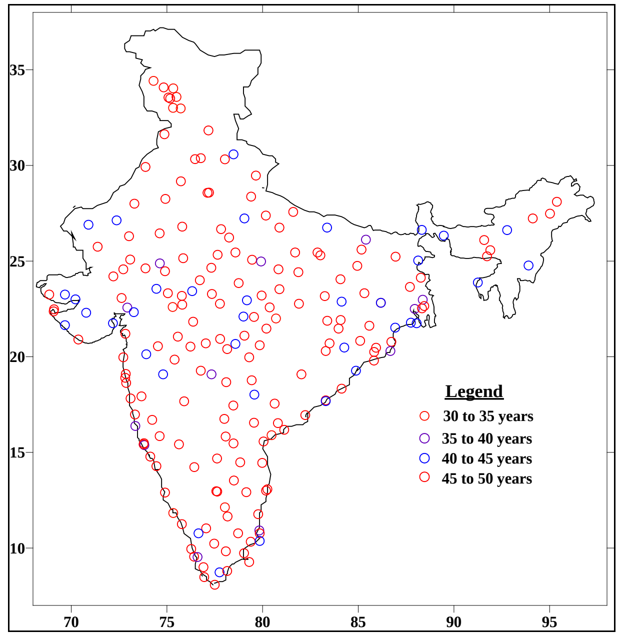


Fig. 1. Geographical locations of 215 surface meteorological stations used for study

least square method to fit linear trend to annual and seasonal LCC. The significance of the calculated trend was estimated using the Student's *t* - test with 5% significance level. Spatial distributions of annual and seasonal trends in LCC are shown in Figs. 4(a-e) where trends significant at 95% level are marked by an outer circle in black. Further, we have linearly detrended the time series of LCC, T_{MAX}, DTR and NRD for all 215 stations before calculating correlations. Scatter plot of India averaged detrended LCC against T_{MAX}, DTR & NRD are shown in Figs. 5(a-e), 7(a-e) and 9(a-e) respectively. Spatial patterns of correlation coefficients between detrended LCC and T_{MAX}, DTR & NRD are shown in Figs. 6(a-e), 8(a-e) and 10(a-e) respectively.

3. Results and discussion

3.1. *Temporal variations in LCC*

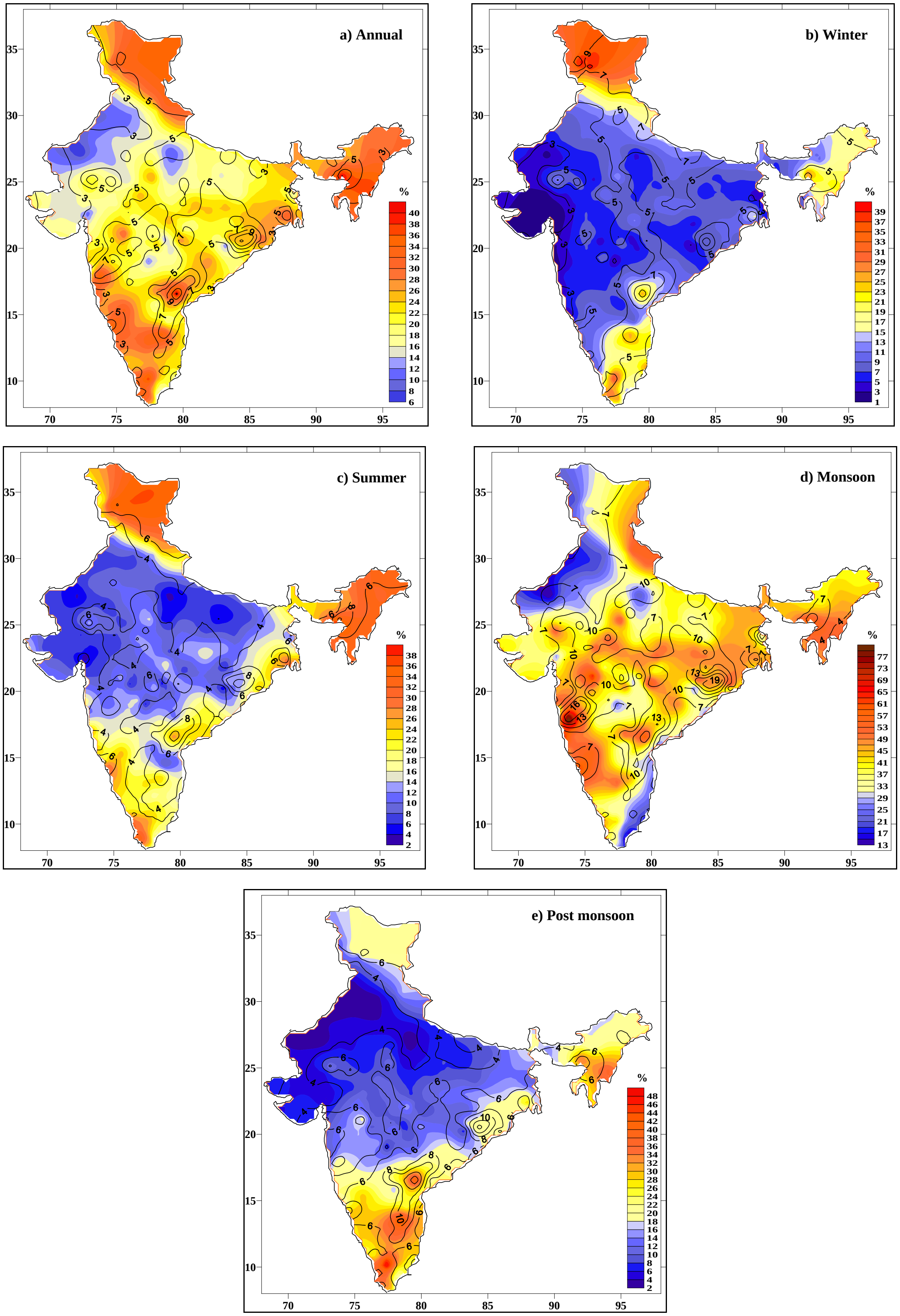
Figs. 2(a-e) shows temporal variations in all India averaged mean annual and seasonal LCC for the period 1961-2010. Mean annual LCC for India is 22.3% which is showing a significantly decreasing trend at the rate of -0.45% per decade. Fig. 2(a) suggests that annual mean LCC has been decreasing steadily since the late 1970s. Time series of annual mean LCC indicates highest LCC (26.4 %) in 1961 and lowest (19.9%) in 1989 as shown in Fig. 2(a). Seasonal mean LCC values are 10.5%, 15.6%, 39.4% and 15.9% for winter, summer, monsoon and post monsoon respectively. The highest cloudy winter season in India was in 1998 with mean LCC 15.2% and lowest

Figs. 2(a-e). Temporal variations in all India low cloud cover (LCC) for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon during 1961-2010. Dashed line in blue indicates long term mean while linear trend line is shown in red

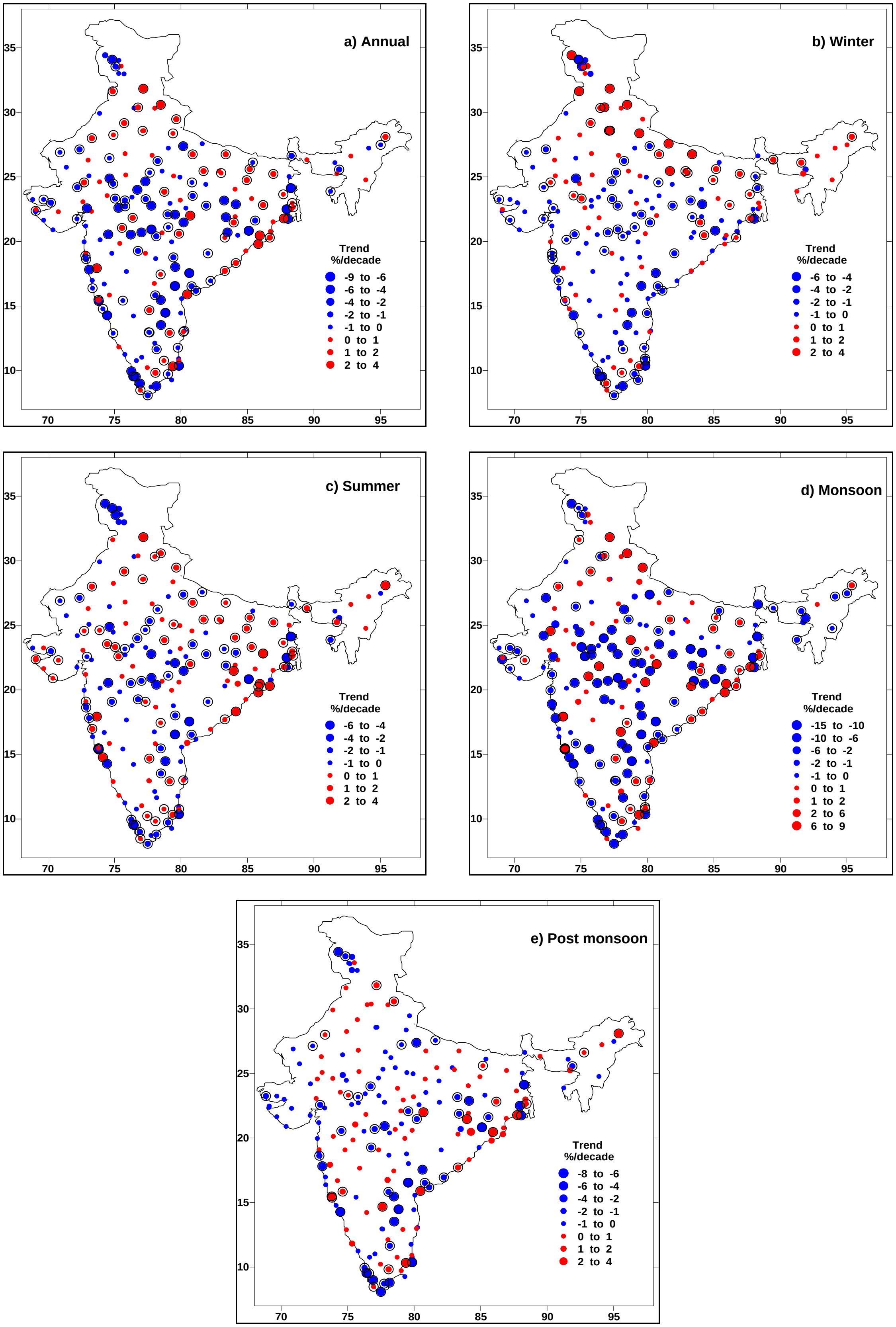
was in 1976 having mean LCC 7.3%. Summer season low cloud cover was highest in 1990 (18.7%) and lowest was 13.1% in 1979. In monsoon season, the highest LCC was obtained in 1961 (46.7%) while lowest cloud cover was in 2009 (33.5%). It is evident from Fig. 2(d) that mean LCC for monsoon has been steadily declining since the mid 1980s. For post monsoon season LCC was highest in 1979 (21.1%) and lowest in 1988 (11.5%). Seasonal LCC trends are decreasing for all seasons but it is significant for monsoon season only. The rate of decline in monsoon season LCC is -1.22% per decade as shown in Fig. 2(d). Annual and seasonal temporal variations as shown in Figs. 2(a-e) indicate consistent lower LCC during last two decades of the data period.

3.2. *Annual and seasonal mean LCC variation*

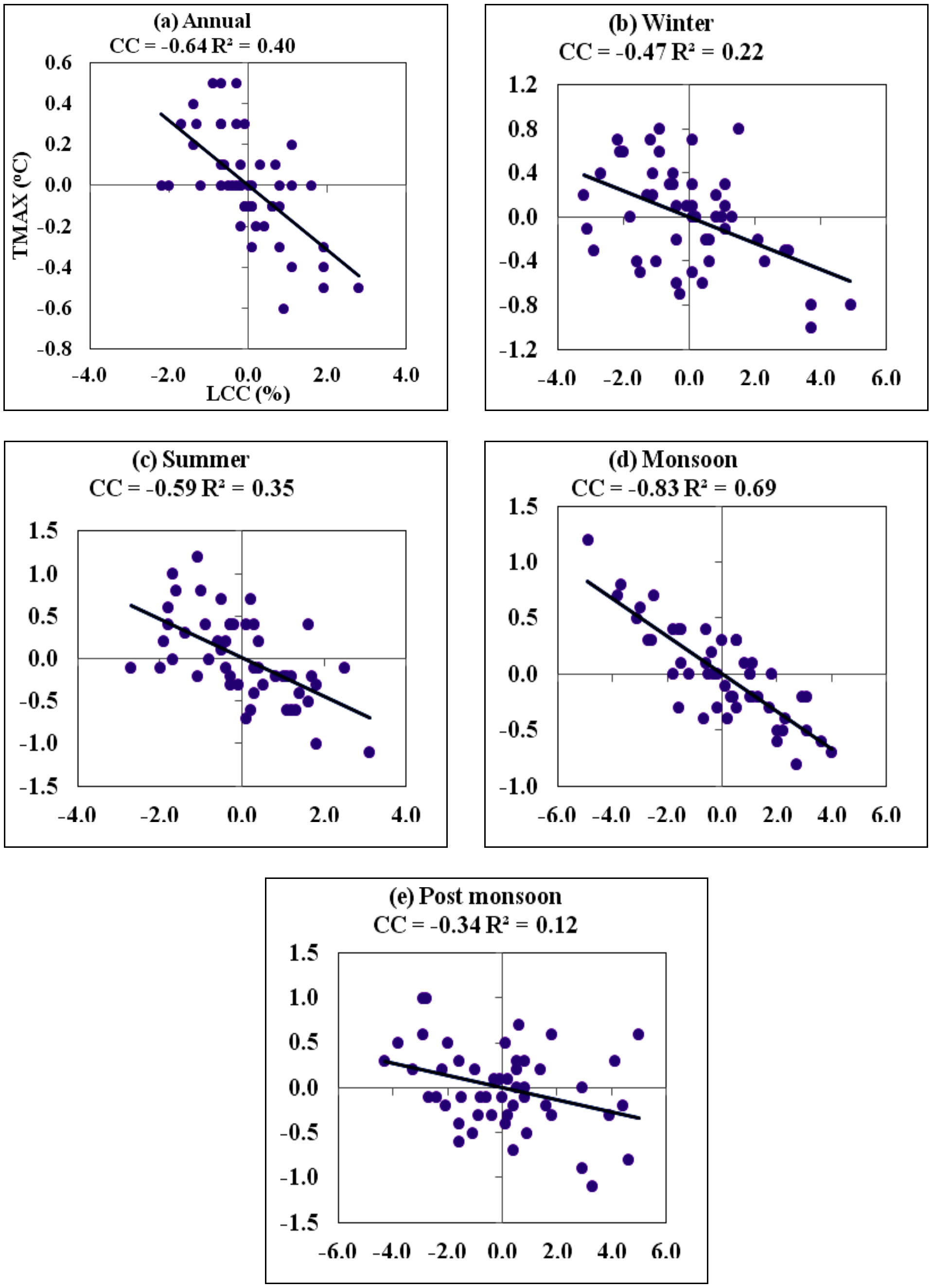
Variability of cloudiness not only affects the climate but also points to atmospheric circulations and processes taking part within the troposphere. Different types of low clouds are created under different atmospheric conditions and their presence indicates specific conditions in the



Figs. 3(a-e). Spatial patterns of mean low cloud cover (LCC) for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon. Contours are standard deviations (%) while long-term mean LCC is shaded



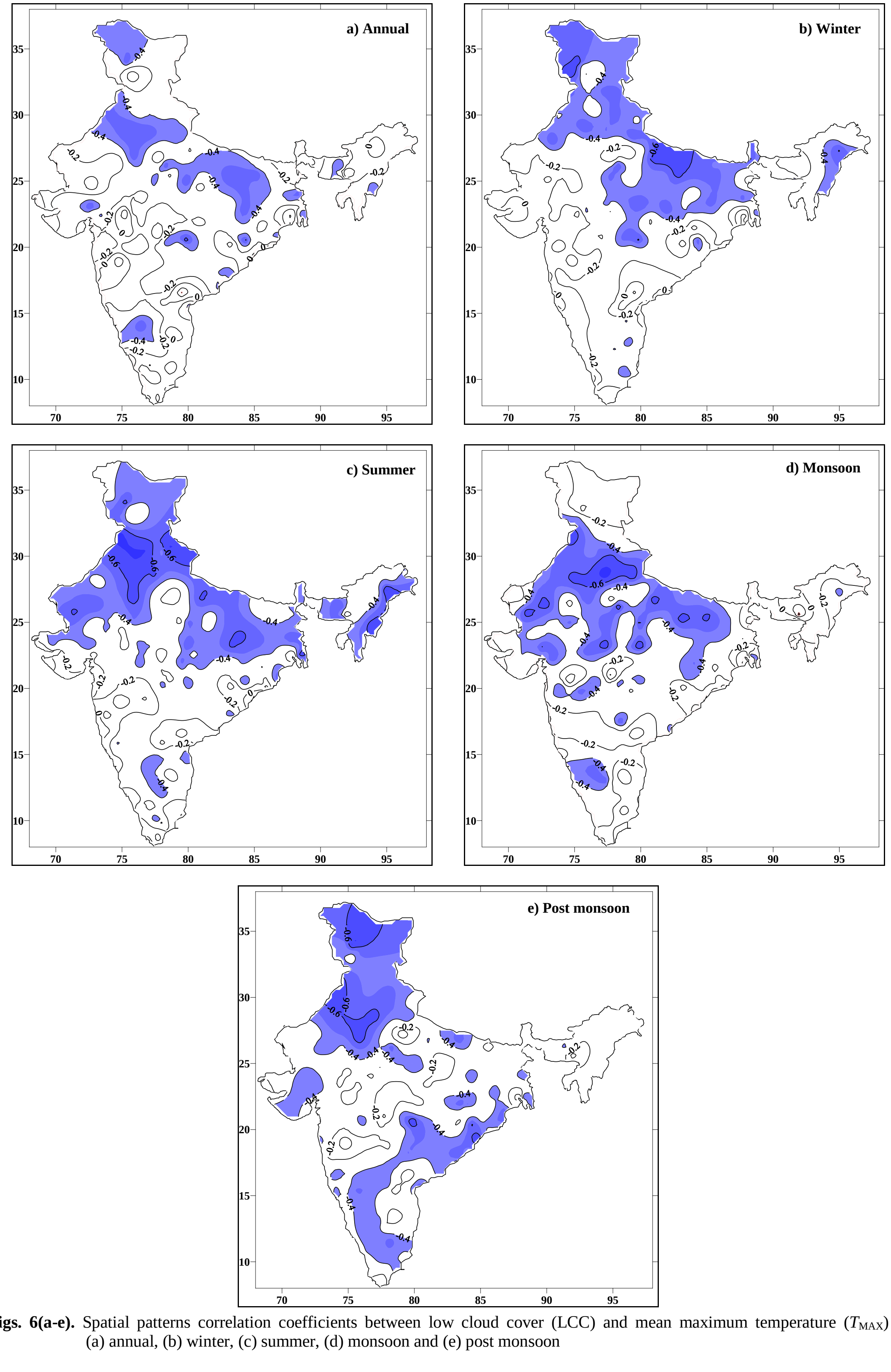
Figs. 4(a-e). Spatial patterns of trends in mean low cloud cover (LCC) for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon



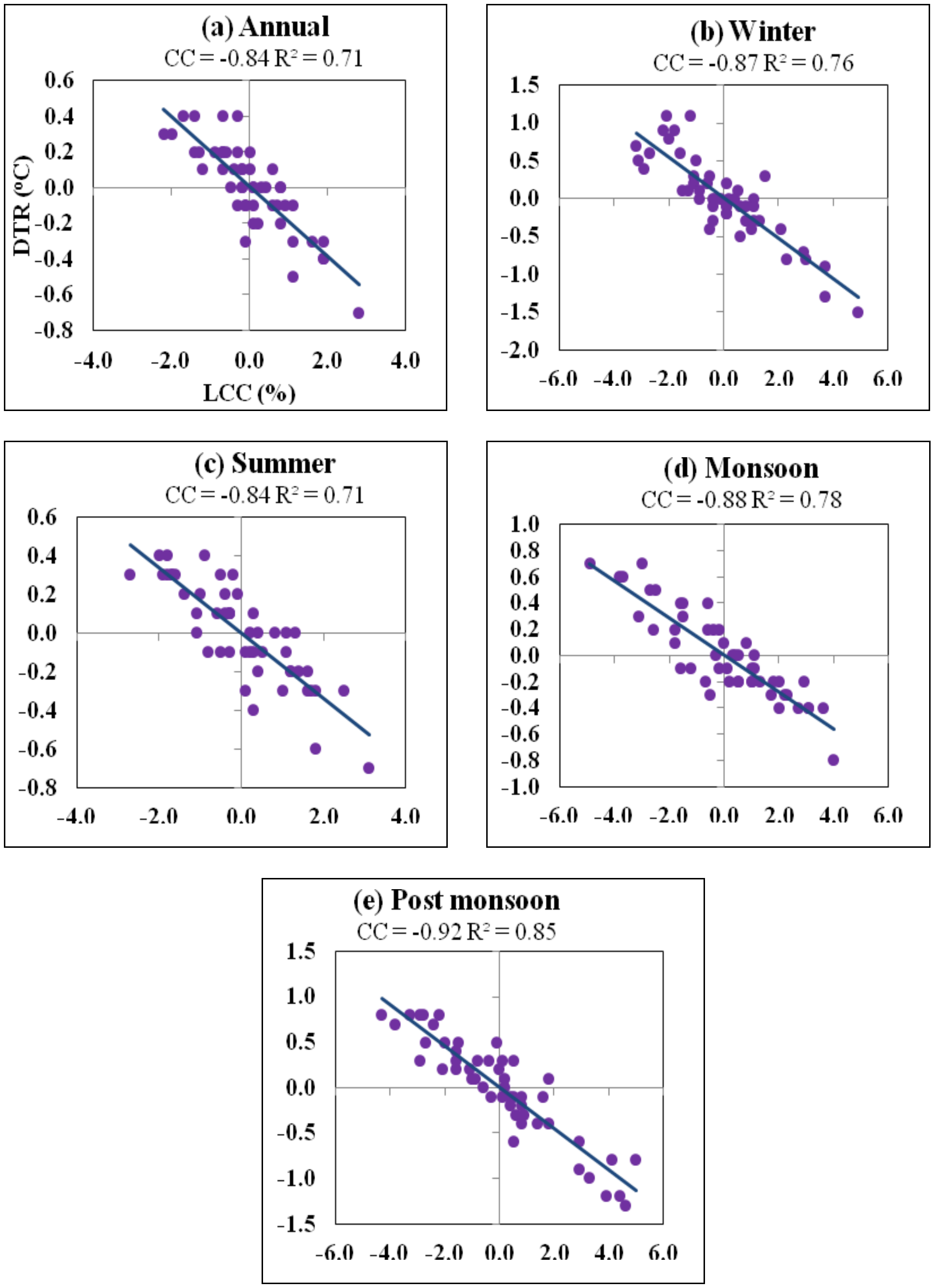
Figs. 5(a-e). Scatter plot of all India mean low cloud cover (LCC) and mean maximum temperature (T_{MAX}) for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon. Data series are linearly detrended for 1961-2010

troposphere *viz*., lower tropospheric stability, upward or downward motion, weak or strong inversion, strong lapse rate and high humidity.

Spatial distribution of long term mean LCC over India based upon 1961-2010 period is shown in Figs. 3(a-e). The patterns of annual mean LCC indicate region of highest low cloud over Western Himalayas, northeast and over west coasts and south interior peninsula [Fig. 3(a)]. Annual mean LCC is highest with lower standard deviations at stations like Cherrapunji, Rentachintala, Bangalore, Mahabaleshwar, Srinagar, Shillong which have more than 35% mean low cloud cover. Western and central India is having lowest annual mean low cloud and highest standard deviation where some stations such as Phalodi, Mainpuri, Jaisalmer and Sri Ganganagar



Figs. 6(a-e). Spatial patterns correlation coefficients between low cloud cover (LCC) and mean maximum temperature (T_{MAX}) for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon



Figs. 7(a-e). Scatter plot of all India mean low cloud cover (LCC) and diurnal temperature range (DTR) for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon. Data series are linearly detrended for 1961-2010

have <10% mean low cloud cover. Similar to annual, seasonal standard deviations in LCC are highest (lowest) where mean LCC is lowest (highest). Winter season LCC is highest in Western Himalayas, extreme northeast and southeast peninsula while rest of the country is having lowest LCC as shown in Fig. 3(b). Summer season LCC are highest over Western Himalayas, northeast, south peninsula and along west and east coasts of India as shown in Fig. 3(c). Highest LCC over India is during monsoon season when entire country except western Rajasthan, parts of Punjab and Jammu and Kashmir and eastern Tamil Nadu is having low cloud cover above 30%. Stations in Western Ghats, Chhattisgarh and northeast India have highest low clouds. The highest monsoon season mean LCC is in Mahabaleshwar (85.2%) while lowest LCC is in Tuticorin (5.6%). Post monsoon season

TABLE 1

Number of stations having decreasing/increasing trends of low cloud cover (LCC) during 1961-2010 for annual, winter, summer, monsoon and post monsoon

Trends	Number of stations				
	Annual	Winter	Summer	Monsoon	Post monsoon
Decreasing	132	132	111	134	126
Significantly decreasing	86	62	59	95	47
Increasing	83	83	104	81	89
Significantly increasing	47	34	58	43	21

TABLE 2

Number of stations having positive/negative correlation between low cloud cover (LCC) and diurnal temperature range (DTR), mean maximum temperature (T_{MAX}) and number of rainy days (NRD) for annual, winter, summer, monsoon and post monsoon

Variable	Sign of correlation	Number of stations				
		Annual	Winter	Summer	Monsoon	Post monsoon
LCC & T_{MAX}	Positive	63	39	46	32	26
	Negative	152	176	169	183	189
LCC & DTR	Positive	63	29	41	51	29
	Negative	152	186	174	164	186
LCC & NRD	Positive	174	204	196	181	194
	Negative	41	11	19	34	21

to LCC is highest in south peninsula and northeast India. While Kodaikanal, Arogyavaram and Rentachintala are having >40% LCC, stations in west and central India such as Sri Ganganagar, Mainpuri, Phalodi, Hissar and Patiala have lower than 3% mean LCC for post monsoon season.

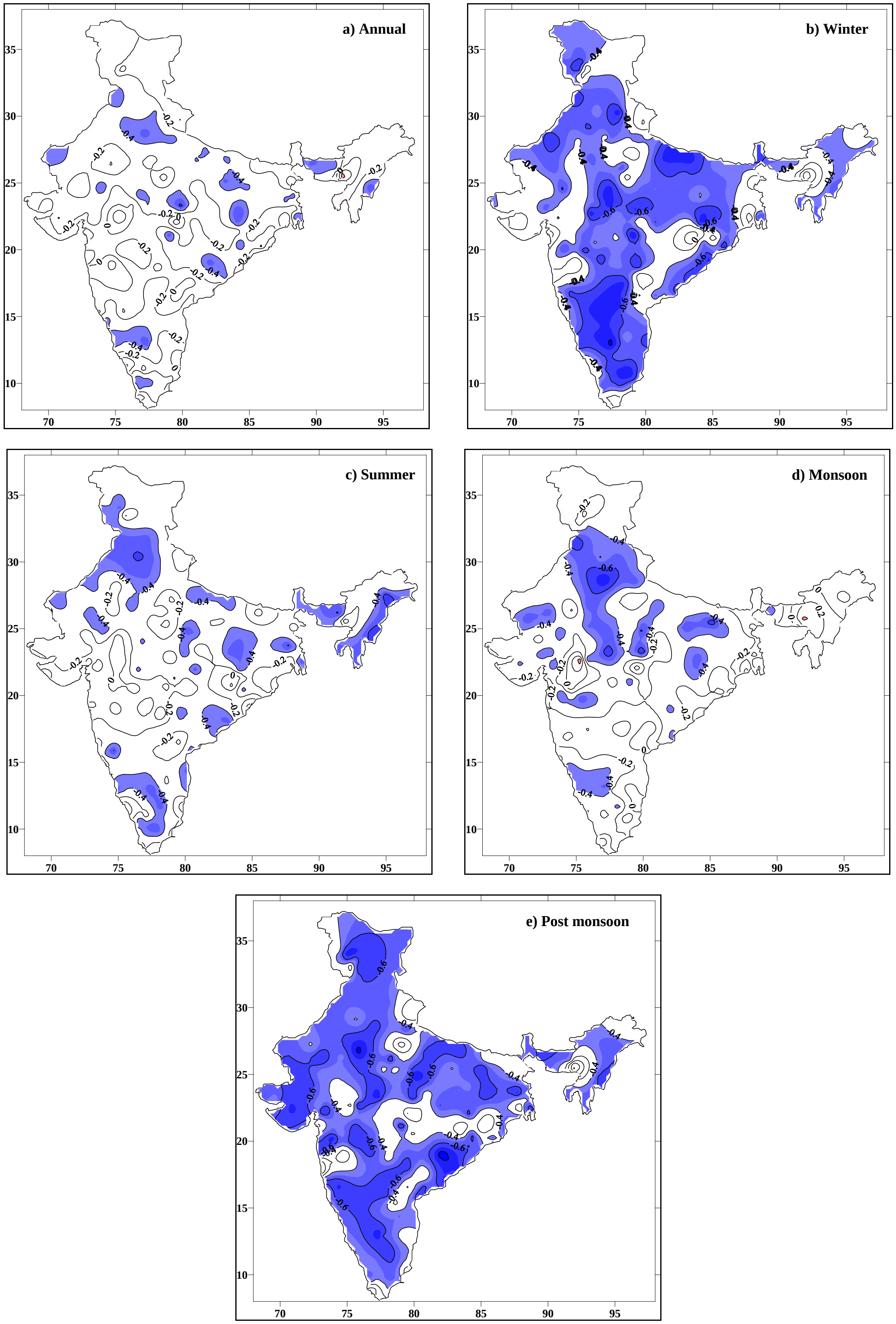
3.3. *Spatial patterns of annual and seasonal LCC trends*

3.3.1. *Annual*

Out of 215 stations selected for study, 132 stations are exhibiting decrease in LCC out of which trends for 86 stations are significant at 95% level of confidence as given in Table 1. However, LCC trends are significantly increasing at 47 stations which are mainly located in the northwest, Indo-Gangetic plains and east coast of India. Spatial distribution of annual LCC trends indicates overall decrease in cloud cover over the as shown in Fig. 6 (a). Stations showing significant decreasing trends in LCC are more coherent over Jammu and Kashmir, central and southeast India and along west coast where rate of decline is in the range of -4% per decade to -9% per decade. However, many stations in northwest India, Indo-Gangetic plains and along east coast of India have significant increasing trends in the range of +2% per decade to +4% per decade. The patterns of annual LCC trends obtained are consistent with trends in total cloud cover reported by Jaswal (2010).

3.3.2. *Winter*

Winter season LCC trends are decreasing at 132 stations out of which trends are significant for 62 stations while numbers of stations having significantly increasing trends are 34 (Table 1). Spatial distribution of winter LCC trends is similar to annual patterns wherein large parts of the country show decline in cloud cover as is clear from Fig. 6(b). Stations showing significant decrease are more coherent over central India, southeast peninsula and along the Indian coastline where many stations have trends in the range -2% per decade to -6% per decade. Winter LCC trends are increasing over Indo-Gangetic plains and northeast India where stations with significant increase in the range of +2% per decade to +4% per decade are located.



Figs. 8(a-e). Spatial patterns correlation coefficients between low cloud cover (LCC) and diurnal temperature range (DTR) for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon

3.3.3. *Summer*

Summer LCC trends are decreasing at 111 stations out of which trends are significant for 59 stations while 58 stations are having significantly increasing trends as given in Table 1. Spatial distribution of trends suggests decrease over Western Himalayas, southeast peninsula, central India and along western coast as shown in Fig. 6(c). Similar to annual and winter season, stations showing significant decrease are more coherent over central India and south peninsula where large number of stations are having trends in the range -2% per decade to -6% per decade. LCC trends are significantly increasing over northwest, northeast, Indo-Gangetic plains and east coast of India where many stations are having trends in the range +2% per decade to +4% per decade.

3.3.4. *Monsoon*

Out of 215 stations, 134 stations are showing decreasing trend in monsoon season LCC. Numbers of stations having significantly decreasing trends are 95 while 43 stations are showing significantly increasing trends in low cloud cover (Table 1). Spatial patterns of trends indicate a general decline in cloud cover over the country except over northwest India where trends are increasing [Fig. 6(d)]. Stations showing significant decrease in monsoon LCC are more coherent over west, east, central and peninsular India where large numbers of stations are having rate of decline more than -6% per decade. In contrast, many stations in the northwest India and hilly regions of Western Himalayas are having significant increasing trends between +4% per decade +9% per decade. Since monsoon season alone contributes to ~70% of annual rainfall, the significant decrease in LCC at large numbers of stations is a cause of worry.

3.3.5. *Post monsoon*

Post monsoon season LCC trends are decreasing at 126 stations out of which trends are significant at 47 stations while the increasing trends are significant at 21 stations as given in Table 1. Spatial pattern of trends suggests a decrease over Jammu and Kashmir, southeast peninsula, central India and along western coast as shown in Fig. 6 (e). Stations showing significant decrease are in southeast peninsula, central India and along west coast where trends are in the range -4% per decade to -8% per decade. Stations showing significant increasing trends in post monsoon LCC are scattered over northwest, northeast, east coast and Tamil Nadu where trends are in the range of +2% per decade to +4% per decade.

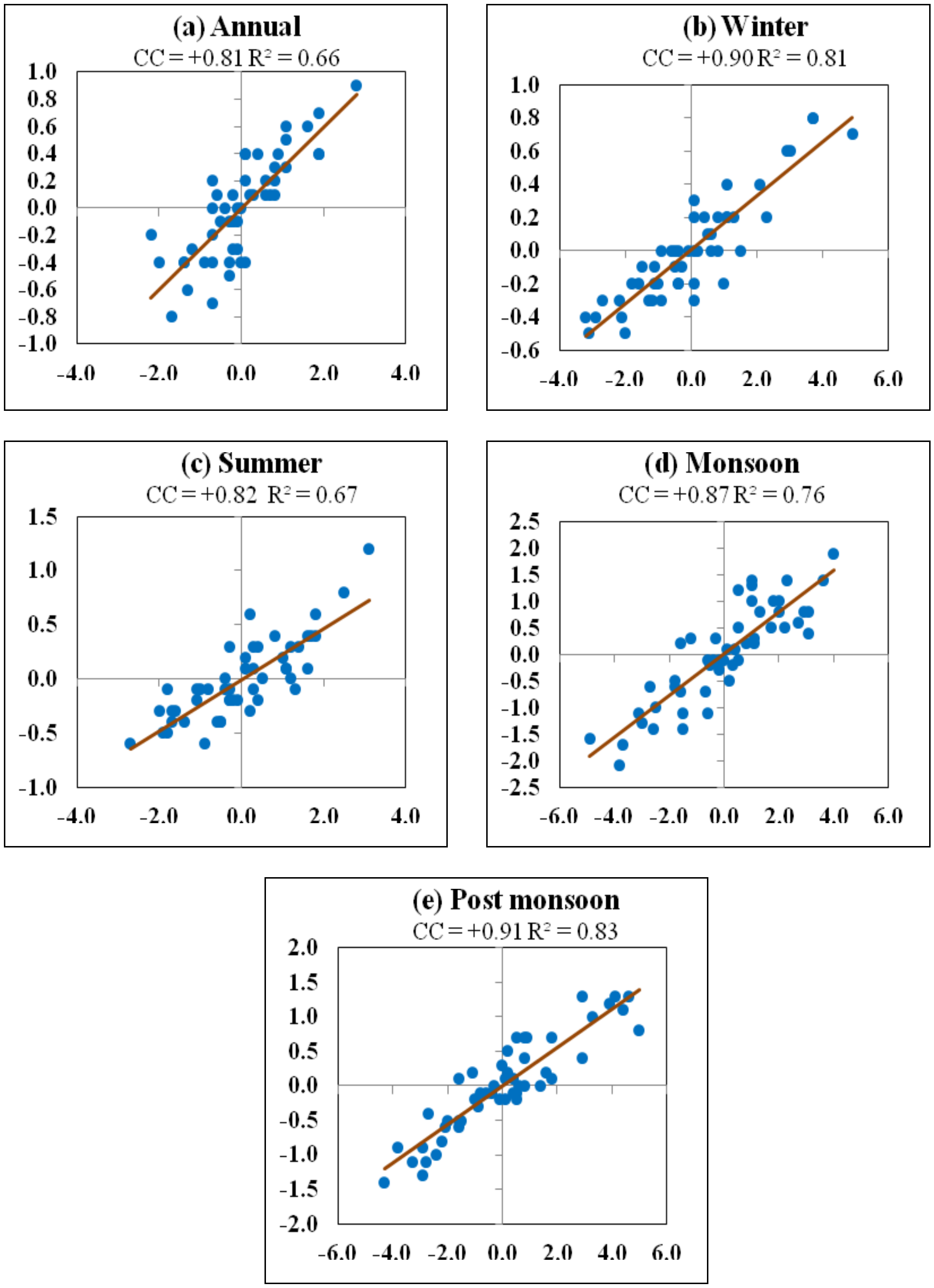
3.4. *Relationship between LCC and associated climatic variables T_{MAX}, DTR and NRD*

Scatter plot of all India averaged detrended time series of annual and seasonal LCC, T_{MAX}, DTR and NRD (Figs. 5, 7 and 9) show relationship between these variables. Reliable cloud observation values should usually have a significant negative relationship with maximum temperature, diurnal temperature range and a significant positive relationship with the number of rainy days. In our study, the regions having significantly negative correlations between LCC & T_{MAX} and LCC & DTR have significantly positive correlations between LCC & NRD suggesting a closer relationship between them.

3.4.1. *Correlation between LCC and T_{MAX}*

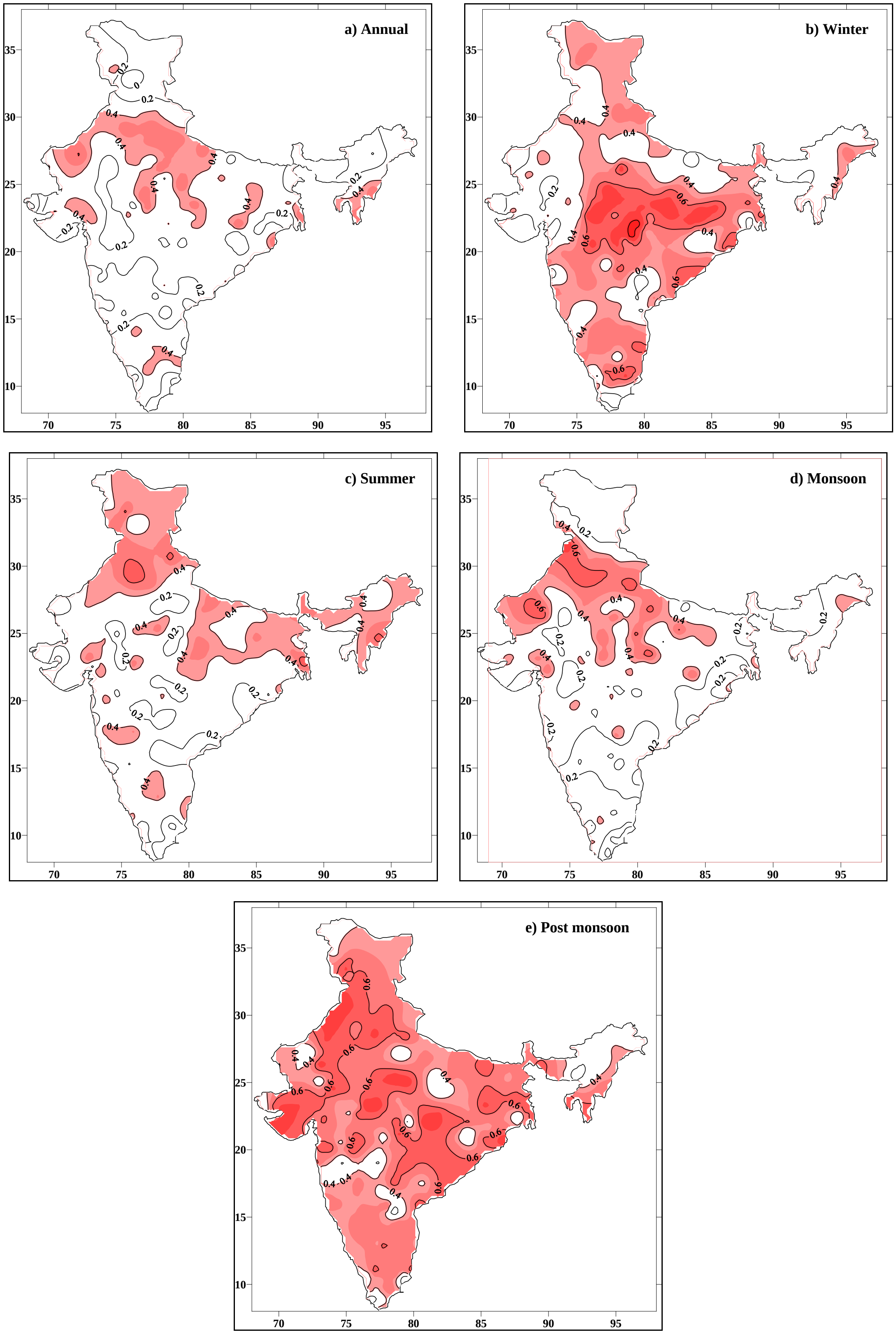
The relationship between detrended mean LCC and T_{MAX} for annual and four seasons during the period 1961 to 2010 is shown in Figs. 5(a-e). The notable feature of this scatter plot is the opposite relationship between LCC and T_{MAX} during all periods indicating significant negative correlation between these two atmospheric parameters as shown in Figs. 5(a-e). Upon comparing the two time series, strong correlations were found in the annual means (-0.64), and also for the different seasons: winter (-0.47), summer (-0.59), monsoon (-0.83) and post monsoon (-0.34). All correlations are significant at the 95% level of confidence. With coefficient of determination (R^2) in the range 0.12 to 0.69, there is strong relationship between these two variables explaining the T_{MAX} variability. It is clear that the higher the correlations, the bigger the influence of LCC on T_{MAX}; indeed the highest values can be found in monsoon and summer followed by winter and post monsoon.

Spatial patterns of correlation between LCC and T_{MAX} is shown in Figs. 6(a-e) where regions having correlation significant at 95% level of confidence are shaded. Correlation between mean LCC and T_{MAX} is negative over most of the country as 71%, 82%, 79%, 85%, 88% stations are negatively correlated for annual, winter, summer, monsoon and post monsoon respectively as given in Table 2 which provides additional confidence in the data utilized in the study. However, the observed coincident decrease in LCC and T_{MAX} or increase in LCC and T_{MAX} over some regions suggests that other mechanisms may have been involved in changing the T_{MAX}. The magnitude of correlation of annual mean LCC and T_{MAX} detrended time series is between -0.68 to +0.43. Shaded region in Fig. 6(a) indicates significantly negative correlation between annual mean LCC and T_{MAX}, which are primarily located in northwest India and over Indo-Gangetic plains. Correlation coefficients of winter



Figs. 9(a-e). Scatter plot of all India mean low cloud cover (LCC) and number of rainy days (NRD) for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon. Data series are linearly detrended for 1961-2010

mean LCC and T_{MAX} time series is between -0.70 to +0.32. Spatial patterns of winter mean LCC and T_{MAX} correlations [Fig. 6(b)] suggest regions of moderate to strong negative correlation over Indo-Gangetic plains, northwest and northeast India. Fig. 6(c) shows spatial patterns of summer mean LCC and T_{MAX} correlation which are moderate to strong over west, northwest and northeast India. Monsoon season mean LCC and T_{MAX} correlations are between -0.80 and +0.47. Spatially, regions of moderate to strong correlations are located over west, northwest, central and south peninsula as shown in Fig. 6(d). Post monsoon season correlation coefficients of LCC and T_{MAX} time series is between -0.76 to +0.17. Post monsoon season mean LCC and T_{MAX} correlation are moderate to strong over northwest India and southeast peninsula as shown by the shaded region in Fig. 6(e).



Figs. 10(a-e). Spatial patterns correlation coefficients between low cloud cover (LCC) and number of rainy days (NRD) for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon

3.4.2. *Correlation between LCC and DTR*

The relationship between mean LCC and DTR for annual and four seasons during the period 1961 to 2010 is shown in Figs. 7(a-e). The notable feature of this scatter plot is the opposite relationship between LCC and DTR indicating significant negative correlation between these two atmospheric parameters as shown in Figs. 7(a-e). Strong correlations were found between LCC and DTR in the annual (-0.84) and also for winter (-0.87), summer (-0.84), monsoon (-0.88) and post monsoon (-0.92) seasons. All correlations are significant at the 95% level of confidence. With coefficient of determination (R^2) in the range 0.71 to 0.88, there is strong relationship between these two variables explaining their variability. It is clear that the higher the correlations, the bigger the influence of LCC on DTR. The highest correlation is found in post monsoon followed by monsoon, winter and summer. The relationship between LCC and DTR obtained here are similar to what reported by Dai *et al*. (1997). Nonetheless, the relatively strong correlation between observed decreases in all India averaged LCC with increase of DTR supports the notion that the increase in DTR is in response to these physical changes.

Spatial patterns of correlation between LCC and DTR is shown in Figs. 8(a-e) where regions having correlation significant at 95% level of confidence are shaded. Correlation between mean LCC and DTR is negative over most of the country as 71%, 87%, 81%, 76%, 87% stations are negatively correlated for annual, winter, summer, monsoon and post monsoon respectively as given in Table 2 which provides additional confidence in the data utilized in the study. However, the observed coincident decrease in LCC and DTR or increase in LCC and DTR over some regions suggests that other mechanisms may have been involved in changing the DTR. The magnitude of correlation of annual mean LCC and DTR is between -0.69 to +0.66. Shaded region in Fig. 8(a) indicates significantly negative correlation between annual mean LCC and DTR. Correlation coefficients of winter mean LCC and DTR is between -0.90 to +0.50. Spatial patterns of winter mean LCC and DTR correlations [Fig. 8(b)] suggest regions moderate to strong negative correlation over all over India. Summer season correlation coefficients between LCC and DTR are between -0.71 and +0.47. Fig. 8(c) shows spatial patterns of summer mean LCC and DTR correlation which have moderate to strong correlation over northwest, northeast and south peninsula. Monsoon season mean LCC and DTR correlations are between -0.81 and +0.57. Spatially, regions of moderate to strong correlations are located over northwest, central, west and south peninsula as shown in Fig. 8(d). Post monsoon season correlation coefficients of LCC and DTR are between -0.87 to +0.59. Moderate to strong correlation between post monsoon season LCC and DTR is seen over almost entire country [Fig. 8(e)].

3.4.3. *Correlation between LCC and NRD*

When averaged over large areas at longer time scales, precipitation should be well correlated with cloudiness (Dai *et al*., 1999). The notable feature of Figs. 9(a-e) is the similar relationship between LCC and NRD during all period (annual and seasonal) indicating significant positive correlation between these two atmospheric parameters. All India NRD is decreasing for annual and four seasons but significant for annual (-0.07 days per decade) and monsoon season (-0.23 days per decade) only. However, the coefficient of correlation between annual LCC and NRD is 0.81 which is highly significant. The coefficients of correlation between seasonal LCC and NRD are 0.90, 0.82, 0.87 and 0.91 for winter, summer, monsoon and post monsoon respectively which are significant at 95% level. With coefficient of determination (R^2) in the range 0.66 to 0.81, there is strong relationship between these two variables explaining their variability during the period of study. As shown in Figs. 9(a-e), the time series of number of rainy days are well correlated with those of low cloud cover which is similar to the results obtained by Wang *et al*. (1993) and Sun *et al*. (2001).

Spatial patterns of correlation between LCC and NRD is shown in Figs. 10(a-e) where regions having significant correlation at 95% level of confidence are shaded. Correlation between mean LCC and NRD is positive over entire country as more than 80% stations are positively correlated for all period as given in Table 2. Annual mean LCC and NRD correlations are between -0.28 and +0.65. Spatial patterns in Fig. 10(a) indicates regions of moderate to strong correlation between annual LCC and NRD which are primarily located in northwest, central, west and northeast India. Winter mean LCC and NRD correlations are between -0.11 and +0.86. Fig. 10(b) shows region of moderate to strong positive correlations between winter LCC and NRD over almost all regions of India. Summer season LCC and NRD correlation coefficients are between -0.19 and +0.69 and regions of moderate to strong correlations are over Western Himalayas, northwest and northeast India, West Bengal and parts of Karnataka as shown in Fig. 10(c). Monsoon season correlation coefficients between LCC and NRD are between -0.21 and +0.76. Spatial patterns of monsoon season mean LCC and NRD correlations [Fig. 10(d)] suggests regions of moderate to strong positive correlation are located over northwest, west and central India. Post monsoon season mean LCC and NRD correlations coefficients range between -0.09 and +0.80 with almost entire country having moderate to strong positive correlation as indicated by shaded region in Fig. 10(e).

Annual and seasonal trends in low cloud cover over India and their relationship with climatic variables maximum temperature, diurnal temperature range and rainy days are investigated for 1961-2010. For country as a whole, statistically significant decrease in LCC has occurred during annual (-0.45% per decade) and monsoon (-1.22% per decade). The LCC trends obtained for India are similar to total cloud cover trends for India reported by Jaswal (2010) as well as global trends reported by Kaiser (2000), Qian *et al*. (2006), Dai *et al*. (2006) and Warren *et al*. (2007). Spatially, the strongest and most consistent evidence for decreasing LCC over India during 1961-2010 is seen over central India and along west coast of India where rate of decrease is in the range -4% per decade to -6% per decade. However, Indo-Gangetic plains is having significant increase in LCC where some stations are having rate of increase in the range +4% per decade to +8% per decade. Due to the profound influence of clouds on both the water balance and global radiation budget, even small variations can alter the climate response. Since monsoon season alone contributes to ~70% of annual rainfall, the significant decrease in LCC as well as NRD in monsoon season during 1961-2010 obtained in this study is a cause of worry.

Further, it is found that for most cases, mean annual and seasonal LCC are significantly negatively correlated with annual and seasonal mean T_{MAX} and DTR and significantly positively correlated with annual and seasonal NRD, providing additional confidence in the data utilised in the study. Clouds affect surface temperature, and surface temperature can also affect cloud development (Warren *et al*., 2007). Durre and Wallace (2001) reported that the spatial patterns of DTR trends are physically consistent with the pattern of trends in cloud cover areas. In our study also, areas of moderate to strong negative correlations between LCC and T_{MAX} & DTR have significant decreasing trends in LCC. Similarly, areas of moderate to strong positive correlations between LCC and NRD have significant increasing trends in LCC. Almost all the cases of LCC decreases were in moderate and negative relationship with T_{MAX} and DTR and in moderate and positive relationship with NRD. As is clear from Figs. 10(a-e), time series of number of days with precipitation are well correlated with those of low cloud cover over India during 1961-2010. At present, it is not known whether changes in cloudiness will exacerbate, mitigate, or have little effect on the increasing global surface temperature caused by anthropogenic greenhouse radiative forcing. Due to their high albedo low clouds have cooling effect, whereas high clouds trap outgoing infrared radiation contributing to warming of Earth's surface (Mace *et al*., 2006; Zelinka and Hartmann, 2010). The decreased cloud cover enhances incoming solar radiation during the day and accelerates outgoing longwave radiation at night, which can lead to increase in daily maximum temperature and reduction in daily minimum temperature. Similarly, decreased cloud cover reduces chances of precipitation. The decrease in low cloud cover may have a large bearing on agriculture and water availability. On the other side, high daytime temperatures and low nighttime temperatures are a major constraint to crop productivity and human health. Crop yields would be negatively affected owing to increased insect and all kinds of pathogens, which are likely to occur with increasing temperature. Further work is required to understand factors contributing to changes in cloud cover over India.

4. Conclusions

About 60% of the world is coved by cloud and cloud is an important factor for weather prediction and climate change. Low-level clouds have a strong effect on Earth's radiative budget for they effectively reflect incoming solar radiation with only a small influence on outgoing longwave radiation (Wood, 2012). However, since many of the physical processes controlling low-level clouds remain obscure, they are one of the prime contributors to the uncertainties of climate model projections (Bony and Dufresne, 2005; Sherwood *et al*., 2014). In summary, the mechanism contributing to the increasing/decreasing low cloud cover over India is unknown and uncertain at present. One factor causing decrease in low cloud cover may be the direct effect of aerosols. As aerosols can cool the Earth's surface by reflecting sunlight and warm the aerosol layer by absorbing downward longwave radiation, the lapse rate will decrease and atmospheric stability will increase, suppressing cloud formation and reducing the cloudiness (Dai *et al*., 1997; IPCC, 2007). Analysis of low cloud cover carried out in this investigation provides spatially and temporally detailed results for India based upon long term quality checked data. The results of this study are summarized as follows:

(*i*) The data analysis indicates that there has been a general decline in mean daily low cloud cover over most parts of the country during past 50 years (1961-2010), but increase in the Indo-Gangetic plains and northeast India. All India averaged annual and seasonal low cloud cover trends are decreasing for all periods but statistically significant for annual (0.45% per decade) and monsoon (1.22% per decade) only.

(*ii*) Out of 215 stations under study, annual low cloud cover has decreased at 61% of the stations out of which 65% are significant at 95% level. On the seasonal scale, the maximum spatial extent for decreased cloud cover has occurred during monsoon (at 62% stations) followed by winter (at 61% stations), post monsoon (at 59% stations) and summer (at 51% stations).

(*iii*) Seasonally, the declining trends in low cloud cover are statistically significant at 47%, 53%, 71% and 37% stations during winter, summer, monsoon and post monsoon respectively.

(*iv*) Spatially, central India, southeast peninsula and west coast has significant decrease in low cloud cover in monsoon season while northwest India and Indo-Gangetic plains have significant increase in low cloud cover during winter and summer seasons.

(*v*) Low cloud cover variability with related meteorological parameters maximum temperature, diurnal temperature range and numbers of rainy days is physically consistent during the period of study. Areas of moderate to strong negative correlations between low cloud cover and maximum temperature and low cloud cover and diurnal temperature range have significant decreasing trends in low cloud cover for all period. Similarly, areas of moderate to strong positive correlations between low cloud cover and number of rainy days have significant increasing trends in low cloud cover for all periods.

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