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Sunshine duration climatology and trends in association with other climatic factors over India for 1970-2006

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सार – इस शोध–पत्र में वर्ष 1970–2006 तक की अवधि के आँकड़ों के आधार पर भारत में बादलों की कुल मात्रा, वर्षा वाले दिनों और अच्छी दृश्यता वाले दिनों से सम्बद्ध धूप खिली रहने की अवधि में हो रहे परिवर्तनों की जाँच की गई है। जलवायु के दृष्टिकोण से, पश्चिमी राजस्थान और उसके समीपवर्ती गुजरात में धुप खिली रहने की कुल वार्षिक अवधि 3100 घंटे से अधिक पाई गई है जो इन क्षेत्रों सौर ऊर्जा के प्रयुक्त किए जाने के लिए उपयुक्त होती है। प्रवृति विश्लेषण से पता चला है कि सभी महीनों में (जून को छोड़कर) देश में धूप खिली रहने की अवधि में उल्लेखनीय रूप से कमी आई है तथा अधिकतम कमी जनवरी के महीने में (–0.44 घंटा प्रति दशक) और उसके बाद दिसम्बर के महीनें में (–0.39 घंटा प्रति दशक) देखी गई है। ऋतु के दृष्टिकोण से शीतऋतु तथा मानसून के बाद (4 प्रतिशत प्रति दशक) धूप खिली रहने की अवधि में कमी सबसे अधिक और मानसून ऋतु में (3 प्रतिशत प्रति दशक) सबसे कम देखी गई है। दशकीय भिन्नताओं से यह पता चला है वर्ष 1990–1999 के दौरान भारत के गांगेय के मैदानी भागों तथा दक्षिणी प्रायद्वीप क्षेत्रों में धूप खिली रहने की अवधि मे अधिकतम कमी आई है। स्थानिक रूप से, भारतीय गांगेय की मैदानी भागों तथा दक्षिणी प्रायद्वीप में धूप खिली रहने की अवधि में अधिकतम कमी की प्रवृत्ति देखी गई है जबकि राजस्थान एवं गुजरात के क्षेत्रों मे न्यूनतम कमी की प्रवृत्ति देखी गई है। इस अध्ययन के अंर्तगत 40 स्टेशनों में से दिल्ली में (शीतऋतु में 13 प्रतिशत प्रति दशक और मानसून के बाद 10 प्रतिशत प्रति दशक) और वाराणासी में (ग्रीष्म एव मानसून में 7 प्रतिशत प्रति दशक) धूप खिली रहने की अवधि में अधिकतम कमी देखी गई है। बादलों की कुल मात्रा, वर्षा के दिनों और अच्छी दृश्यता वाले दिनों के साथ धूप खिली रहने की अवधि के सहसंबंधों का विश्लेषण करने से पता चला है कि देश में धूप खिली रहने की अवधि में दीर्घावधि प्रवृति को दर्शाने वाले कारकों में क्षेत्रीय एवं मौसमीय भिन्नताएँ होती हैं।

ABSTRACT. Changes in sunshine duration in association with total cloud amount, rainy days and good visibility days over India were examined for 1970-2006. Climatologically, annual total sunshine duration over west Rajasthan and adjoining Gujarat is more than 3100 hours which is ideal for harnessing solar energy over these regions. The trend analysis indicates significant decrease in sunshine duration over the country for all months (except June) and the maximum decrease has taken place in January (-0.44 hour/decade) followed by December (-0.39 hour/decade). Seasonally, decline in sunshine hours is highest in winter and post monsoon (4% per decade) and lowest in monsoon (3% per decade). Decadal variations indicate maximum decrease in sunshine over the Indo-Gangetic plains and south peninsula during 1990-1999. Spatially, the decreasing trends in sunshine hours are highest in Indo-Gangetic plains and south peninsula while regions over Rajasthan and Gujarat have lowest decrease. Out of 40 stations under study, the maximum decrease in sunshine has occurred at New Delhi (winter at 13% per decade and post monsoon at 10% per decade) and Varanasi (summer and monsoon at 7% per decade). Correlation analysis of sunshine duration with total cloud amount, rainy days and good visibility days indicates regional and seasonal variations in factors explaining the long term trends in sunshine duration over the country.

Key words – Sunshine duration, Total cloud amount, Rainy days, Visibility, Trends, Correlation coefficient, Aerosol.

1. Introduction

Considerable changes in the climate system have been reported globally and many of these changes have been attributed to anthropogenic influences (IPCC, 2007). There were reports of a widespread decrease in global solar radiation between the 1950s and 1980s over the globe (Ohmura and Lang, 1989; Gilgen *et al.*, 1998; Stanhill and Cohen, 2001; Liepert, 2002) and a reversal in this trend has been detected in many regions of the world since 1980 (Pinker *et al.*, 2005; Wild *et al.*, 2005). Thus solar radiation reaching the Earth's surface has become important, since its variation might show some indications of anthropogenic disturbances (Ramanathan *et al.*, 2001). The simplest information about radiation is available from sunshine duration and the knowledge of its variation at earth's surface is of major importance not only from the climatological point of view but also from agriculture, environment and other related scientific/engineering fields.

Decrease in the average amount of sunlight reaching the surface of the earth across the world has been reported by many authors. These studies were done over Australia (Stanhill and Kalma, 1994), Israel (Stanhill and Ianetz, 1996), Hong Kong (Stanhill and Kalma, 1995), Ireland (Stanhill, 1998), Germany (Weber, 1990; Liepert and Kukla, 1997), the United States (Liepert, 2002 and Stanhill and Cohen, 2005), Taiwan (Liu *et al.*, 2002), China (Kaiser and Qian, 2002; Liang and Xia, 2005) and the former Soviet Union (Abakumova *et al.*, 1996). Like in other parts of the world, decrease in radiation and sunshine duration has been reported in India also. Rao *et al.*, (2004) have reported decreasing trends in solar radiation and sunshine duration over India. Ramanathan *et al.*, (2001 and 2005) have studied satellite and ground-based radiation measurements and have found up to 10% decrease in surface shortwave radiation flux due to anthropogenic aerosols over parts of Central India during the non-monsoon season (January to April). Kumari *et al.*, (2007) have found significant decrease in solar radiation over India which they have attributed to increase in aerosol optical depth over the country. The possible causes of reduction in solar irradiance and sunshine duration have been examined world over and now focus has shifted towards aerosol loadings and other anthropogenic pollutants which can affect radiation budget anywhere. Increase in aerosols as the main driving force of decreasing solar radiation and sunshine hours in China has been reported by Zhang *et al.*, 2004 and Qian *et al.*, 2007 and there is significant increase in aerosols and other anthropogenic pollutants over Indian sub-continent as reported by Venkataraman *et al.*, (2005), Dey *et al.*, (2004), Singh *et al.*, (2004), Prasad *et al.*, (2004), Ramanathan *et al.*, (2005), Sarkar *et al.*, (2006) and Biggs *et al.*, (2007).

The purpose of this study is to document changes in sunshine duration over India in recent years and examine the causes on the basis of other climatic variables such as cloudiness, rainy days and horizontal visibility. The decline in sunshine duration and its correlation with other climatic variables are discussed in the end.

2. Data and methodology

2.1. *Sunshine duration measurement*

The term "sunshine" is related to the brightness of the solar disc and is better observed by the human eye with the appearance of shadows behind illuminated objects. Sunshine duration during a given period is the sum of that sub-period for which the direct solar

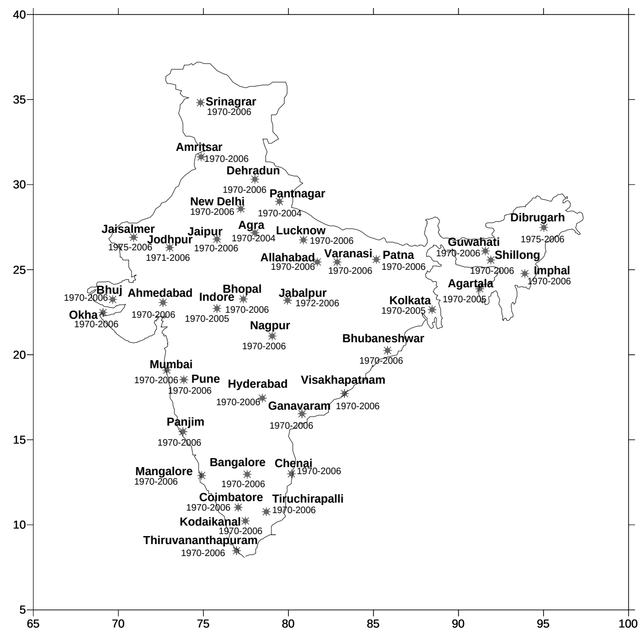


Fig. 1. Geographic location and period of data used for 40 stations selected for study

irradiance exceeds 120 Wm^{-2} (WMO, 2003) and the unit used is hours per day. It is measured in India Meteorological Department (IMD) by a standard instrument called Campbell-Stokes (burn method) sunshine recorder. The Campbell-Stokes sunshine recorder consists essentially of a glass sphere mounted concentrically in a section of a spherical bowl, the diameter of which is such that the sun's rays are focused sharply on a card held in grooves in the bowl. As the earth rotates, the position of the spot moves across the card and a trace is charred. When the sun is obscured, the trace is interrupted. The total length of the burns on the chart (excluding gaps) gives the daily bright sunshine duration.

2.2. *Computation method*

The sunshine duration, total cloud amount, number of rainy days and horizontal visibility data of 40 surface observatory stations located in India as shown in Fig. 1 for the period 1970-2006 were taken from the archives of IMD located at National Data Centre, Pune where all climatological data are processed, quality controlled and archived. Total cloud amount refers to the portion of the sky in eights covered by clouds at any height. A rainy day is defined as a day with precipitation of 2.4 mm or more. Horizontal surface visibility is a measure of transparency of the atmosphere and is affected by fog, cloud, dust storm, precipitation and various kinds of pollutants in the atmosphere. Visibility values are recorded in code ranging from 90 (<0.05 km) to 99 (≥50 km) and good visibility

TABLE 1

All India monthly, annual and seasonal means and trends in sunshine duration (SSH), total cloud amount (CLD), number of rainy days (NRD) and good visibility days (VIS) based for 1970-2006. SSH, CLD, NRD and VIS means are in hour, okta, days and % days respectively while trends are in the same unit per decade

	SSH		CLD		NRD		VIS	
	Mean	Trend	Mean	Trend	Mean	Trend	Mean	Trend
January	7.9	- 0.44**	2.5	+ 0.10	1.1	+ 0.03	16.6	- 5.87**
February	8.6	- 0.26**	2.4	- 0.01	1.4	- 0.01	18.7	- 6.42**
March	8.3	- 0.22**	2.4	+ 0.11*	1.7	+ 0.05	20.0	- 6.73**
April	8.6	- 0.23**	2.9	+ 0.02	2.7	no trend	20.9	- 6.36**
May	8.5	- 0.31**	3.3	+ 0.05	4.3	+ 0.12	20.8	- 5.89**
June	6.1	- 0.10	5.0	- 0.09	8.2	- 0.12	17.9	- 5.30**
July	4.4	- 0.14*	6.2	- 0.06	12.3	- 0.12	16.0	- 5.41**
August	4.7	- 0.13*	6.1	- 0.09*	11.7	- 0.33	16.6	- 5.54**
September	6.1	- 0.16*	5.0	- 0.01	8.3	- 0.06	19.4	- 6.64**
October	7.5	- 0.29**	3.4	+ 0.02	4.7	+ 0.12	19.3	- 7.04**
November	7.8	- 0.32**	2.7	+ 0.02	2.3	- 0.02	17.7	- 6.52**
December	7.6	- 0.39**	2.5	- 0.01	1.2	- 0.07	16.2	- 5.87**
Annual	7.2	- 0.25**	3.7	+ 0.01	5.0	- 0.03	18.3	- 6.16**
Winter	8.1	- 0.37**	2.5	+ 0.03	1.3	- 0.02	17.4	- 6.05**
Summer	8.5	- 0.25**	2.9	+ 0.07*	2.9	+ 0.07	20.6	- 6.31**
Monsoon	5.4	- 0.14**	5.6	- 0.04	10.2	- 0.12	17.5	- 5.75**
Post monsoon	7.7	- 0.31**	3.0	+ 0.02	3.5	+ 0.05	18.5	- 6.78**

* - trends significant at 95% level, ** - trends significant at 99% level

days in this study are defined as days having visibility in code range 97-99 which correspond to >10 km. Total cloud amount and horizontal visibility data are recorded by observers by estimation at surface observatories of IMD at every synoptic hour and for this study data were taken for day-time (average of 0300, 0600, 0900 and 1200 UTC) observations only. Stations having at least 30 years simultaneous sunshine duration, total cloud amount, horizontal surface visibility and rainy days data for the period 1970-2006 and having not more than 10% missing data in between the starting and ending years were selected for this study after omitting stations having large data gaps. Monthly means were first calculated from daily sunshine duration and then annual and seasonal mean sunshine duration (SSH) data series for all stations were prepared. The annual and four seasons are as follows: January to December (annual), December to February (winter), March to May (summer), June to September (monsoon), October to November (post monsoon). Similar to SSH, annual and seasonal data series for total cloud amount (CLD), number of rainy days (NRD) and number of good visibility days (VIS) were also prepared. In this work, CLD and VIS refer to daytime average values of total cloud amount (in okta) and good visibility days (expressed in %) respectively.

From the monthly time series of 40 stations, average India monthly, annual and seasonal SSH, CLD, NRD and VIS data series were prepared for 1970-2006 to examine country as a whole trends. The linear trend analysis was performed on these data series and trends were tested for significance at 95% and 99% level of significance using *t*-test. Average India monthly, annual and seasonal mean and trend values of SSH, CLD, NRD, and VIS are given in Table 1 and monthly variations in means are shown in Fig. 2. Decadal average India means and trends in SSH, CLD, NRD and VIS for 1970-1979 (D1), 1980-1989 (D2),

TABLE 2

Decadal means and trends of sunshine duration (SSH), total cloud amount (CLD), rainy days (NRD) and good visibility days (VIS) for India based upon 40 stations under study. SSH, CLD, NRD and VIS means are in hour, okta, days and % days respectively while trends are in the same unit per decade

		1970-1979		1980-1989		1990-1999		2000-2006	
		Mean	Trend	Mean	Trend	Mean	Trend	Mean	Trend
SSH	Annual	7.5	+ 0.02	7.4	+ 0.02	6.9	- 0.15*	6.8	- 0.25
	Winter	8.6	- 0.41*	8.2	+ 0.05	7.7	- 0.41	7.5	- 0.04
	Summer	8.8	+ 0.20	8.6	+ 0.01	8.3	- 0.04	8.1	- 0.29
	Monsoon	5.5	+ 0.63	5.5	+ 0.04	5.1	+ 0.11	5.2	- 0.14
	Post monsoon	7.9	- 0.86**	8.0	+ 0.12	7.4	- 0.43	7.2	- 0.75*
CLD	Annual	3.7	+ 0.19	3.6	- 0.29*	3.7	+ 0.16	3.7	+ 0.61**
	Winter	2.4	+ 0.22	2.5	- 0.25	2.5	+ 0.24	2.5	+ 0.57
	Summer	2.8	- 0.03	2.9	- 0.21	3.0	- 0.10	3.0	+ 0.68
	Monsoon	5.7	- 0.27	5.5	- 0.30	5.6	+ 0.13	5.6	no trend
	Post monsoon	3.2	+ 0.97**	2.8	- 0.35	3.2	+ 0.47	3.0	+ 0.75*
NRD	Annual	5.1	+ 0.09	4.9	- 0.49	5.1	- 0.05	4.9	+ 0.57
	Winter	1.2	+ 0.28	1.3	- 0.22	1.3	- 0.17	1.1	- 0.07
	Summer	2.8	- 0.01	2.9	- 0.53	2.9	- 0.48	3.1	+ 0.21
	Monsoon	10.4	- 0.51	10.1	- 0.78	10.3	- 0.05	10.0	+ 0.82
	Post monsoon	3.8	+ 0.87	3.0	- 0.19	3.8	+ 1.34*	3.5	+ 2.21*
VIS	Annual	27.0	- 6.46**	20.2	- 5.30**	14.2	- 4.42**	9.3	- 6.96**
	Winter	25.9	- 6.07**	19.2	- 5.82**	13.1	- 4.59**	8.7	- 4.82**
	Summer	29.2	- 5.86**	22.7	- 5.65**	16.7	- 5.15**	10.9	- 8.61**
	Monsoon	25.7	- 6.02**	18.9	- 4.82**	13.5	- 3.68**	9.3	- 5.86**
	Post monsoon	28.1	- 8.83**	20.4	- 5.12**	13.9	- 5.00**	8.8	- 5.75**

* - trends significant at 95% level, ** - trends significant at 99% level

1990-1999 (D3) and 2000-2006 (D4) decades were calculated and are given in Table 2. The spatial patterns of decadal variation in mean SSH as difference of decade D3from D2 for annual and four seasons over India are shown in Figs. 3(a-e). Temporal variations of average India SSH, CLD and NRD for 1970-2006 as anomalies from 1971-2000 means are shown in Figs. 4(a-e). The interannual variation in SSH over India is compared by calculating coefficient of variation (CV) for all stations. The geographical distributions of annual and seasonal means and CVs of SSH are shown in Figs. 5(a-e) where CV patterns are shaded. Annual and seasonal SSH trends for all 40 stations are given in Table 3. Correlation coefficients (CC) of SSH with other climatic parameters CLD, NRD and VIS were analyzed spatially in order to present supporting material indicative of the potential causes of the observed trends in sunshine duration. Spatial analysis of (a) SSH trends (% per decade), (b) CC of SSH with CLD, (c) CC of SSH with NRD and (d) CC of SSH with VIS for annual, winter, summer, monsoon and post monsoon are shown in Figs. 6 to 10 where regions having significant (at 99%) CCs are shaded.

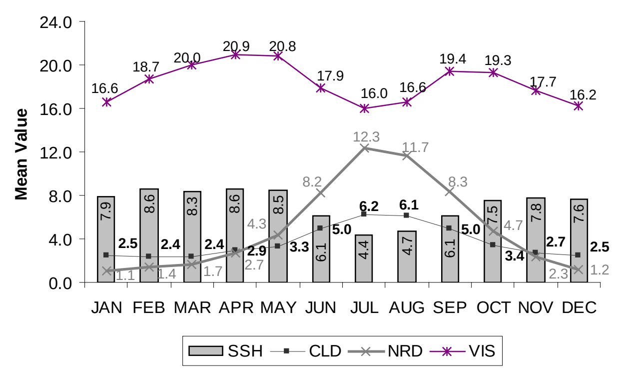
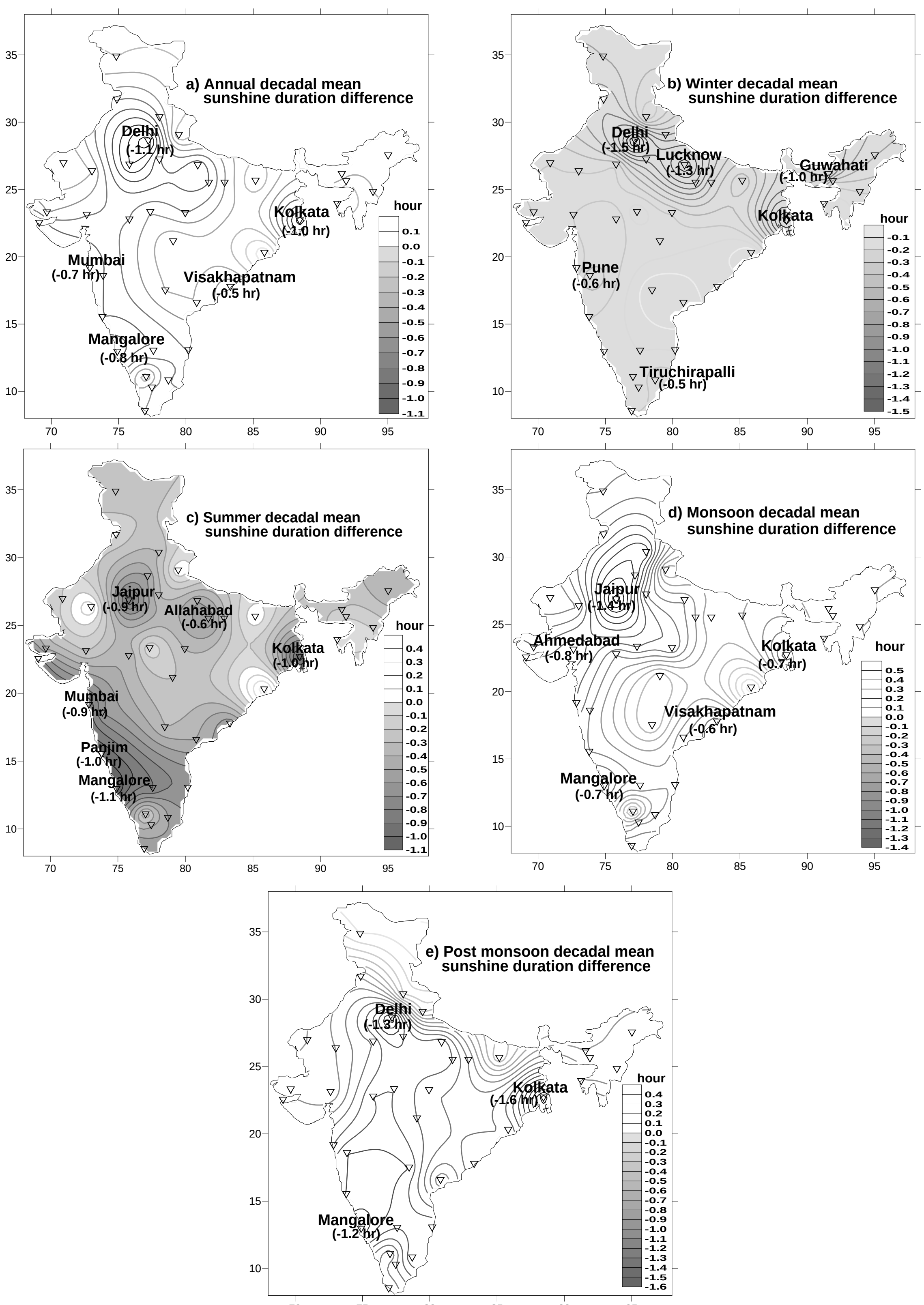
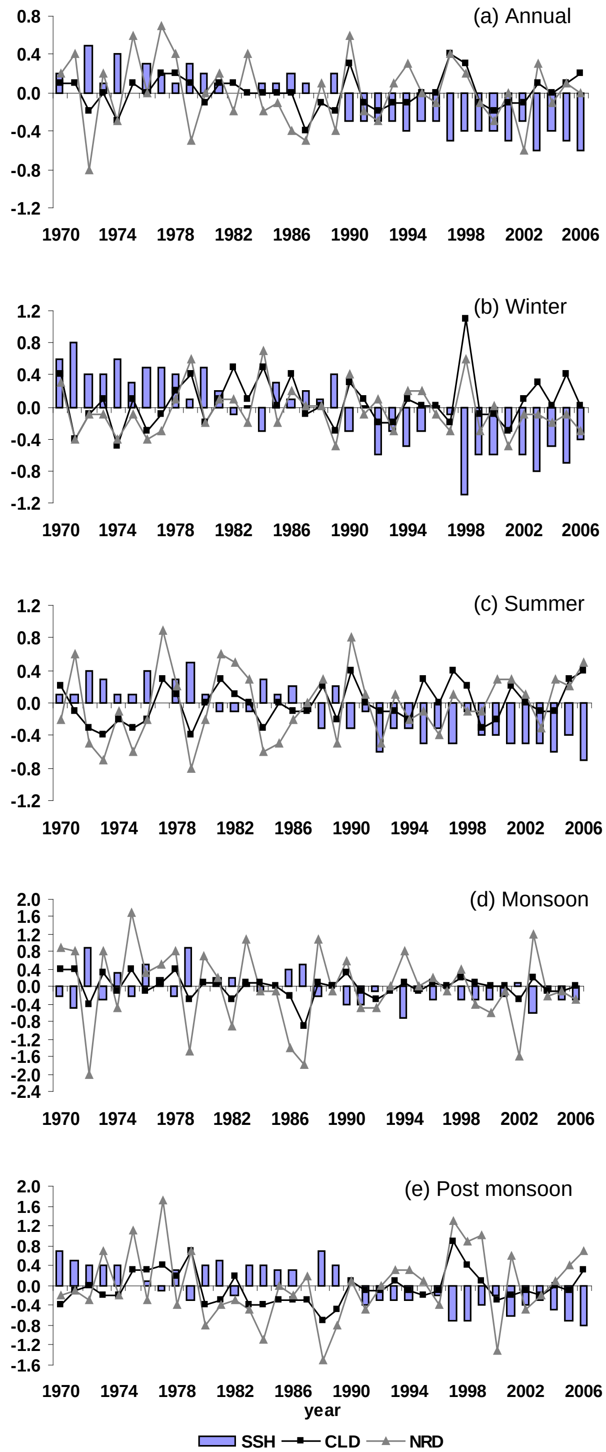


Fig. 2. All India mean sunshine duration (SSH in hours), mean total cloud amount (CLD in okta), number of rainy days (NRD in days) and good visibility days (VIS in % days) based upon 40 stations under study for the period 1970-2006



Figs. 3(a-e). Spatial distribution of difference of mean sunshine duration of decade 1990-1999 from that of 1980-1989 for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon. Regions having negative sunshine duration difference are shaded



Figs. 4(a-e). Temporal variation of sunshine duration (SSH in hour), total cloud amount (CLD in okta) and number of rainy days (NRD in days) for India based upon 40 stations for 1970-2006. Series are anomalies from 1971-2000 average for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon

3. Results and discussion

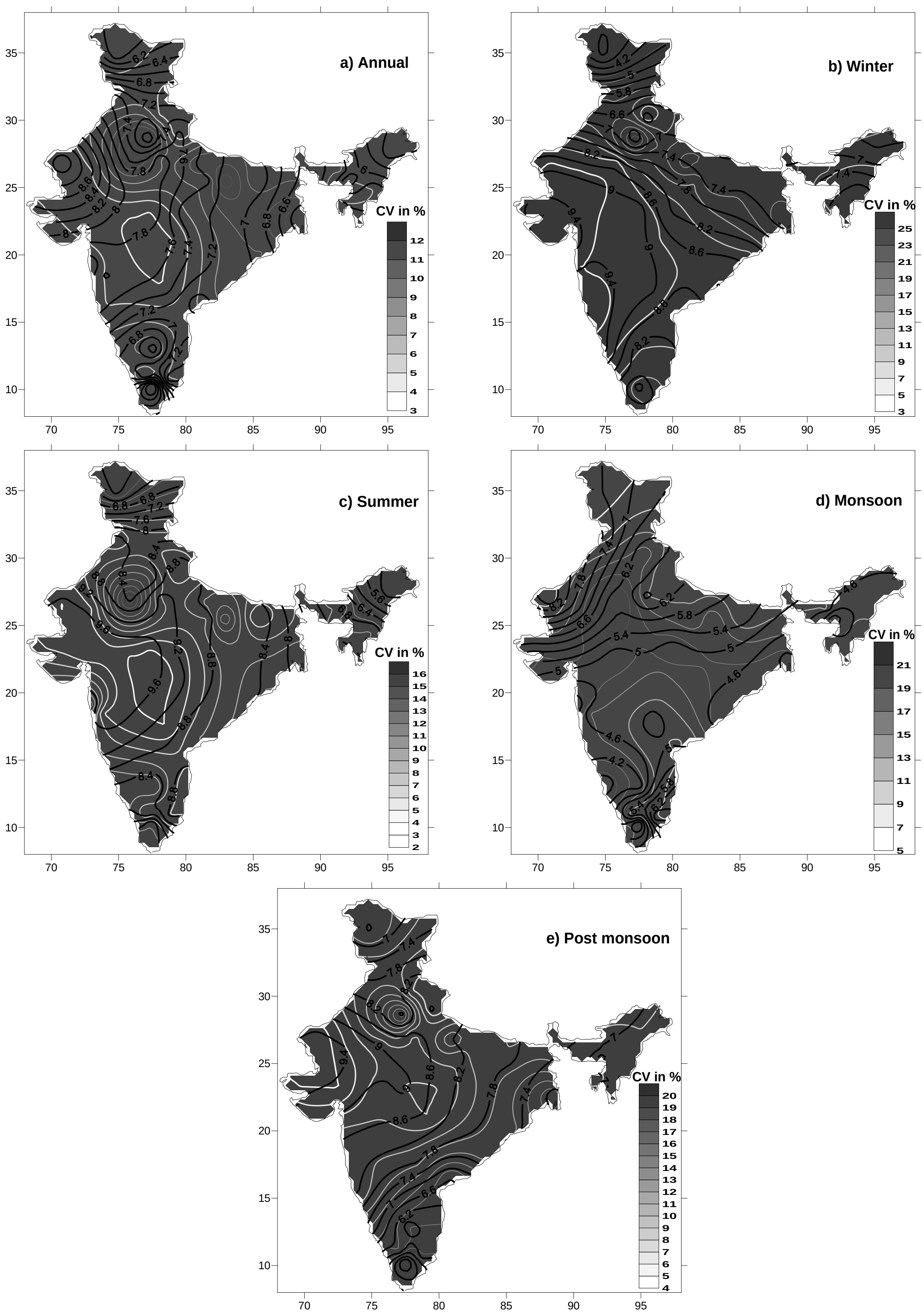
3.1. *Averaged India climatology and trends*

Sunshine is an important climatic factor as it is direct radiation emitted from the sun as opposed to the shading of a location by clouds, aerosols or by any other type of obstructions. It is influenced by other meteorological parameters and usually has a negative relationship with cloud cover and rainy days and a positive relationship with the number of good visibility days and evaporation. Clouds have direct effect on sunshine by blocking incoming solar radiations. Similarly, aerosols and other anthropogenic pollutants also block the incoming solar radiations leading to decrease in sunshine duration.

3.1.1. *All India means and trends*

A detailed examination of Table 1 and Fig. 2 underlines some expected but nevertheless important points. The annual march of hours of sunshine over India appears to follow a simple variation with maximum (minimum) sunshine when CLD and NRD are lowest (highest). Monthly SSH varies between 4.4 hours/day (July) and 8.6 hours per day (February and April) over India. Monthly CLD values are in the range 2.4 okta per day (February and March) and 6.2 okta per day (July). Similarly, monthly rainy days are lowest in January (1.1 days per month) and are highest in the monsoon month July (12.3 days per month). Monthly VIS values are between 16.0% per month and 20.9% per month showing lesser monthly and seasonal variations over the country.

Monthly SSH trends are between -0.44 hours per decade and -0.10 hours per decade and are significantly decreasing for all months except June (Table 1). The decreasing SSH trends are significant at 99% for January to May and October to December while July and August trends are significant at 95%. Similar to monthly SSH trends, annual and seasonal trends are also decreasing significantly at 99% and highest decrease (4% per decade) has occurred in winter and post monsoon which agrees well with the decrease in solar radiation over India reported by Kumari *et al.*, (2007). India averaged monthly CLD trends are weak and are significantly decreasing at 95% for August and increasing significantly at 95% for March. Seasonal trends in CLD are between -0.04 okta per decade and +0.07 okta per decade and is increasing significantly at 95% for summer season. Similar to CLD trends, NRD trends are weak and mixed indicating possibilities of regional or station specific trends in these two parameters. India averaged VIS trends are significantly decreasing at 99% for all periods. The strong decreasing trends in VIS over the country are in agreement with reports of significant increase in aerosol



Figs. 5(a-e). Geographical variation of mean and coefficient of variation (CV) of sunshine duration for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon. Contour lines represent sunshine duration (in hours) while coefficient of variation (in %) is shaded loading over Indian cities (Dey *et al.,* 2004 and Sarkar *et al.,* 2006).

3.1.2. *Decadal variations*

Decadal variations in means and trends of SSH, CLD, NRD and VIS for D1, D2, D3 and D4 decades are shown in Table 2. Annual mean SSH has decreased from 7.5 hours/day to 6.8 hours/day during the four decades. Post monsoon season trend in SSH is significant at 99% level for decade D1. The SSH trends are significant at 95% for annual (D3), winter (D1) and post monsoon (D4) seasons. The decadal changes in mean CLD and NRD do not indicate any significant pattern but VIS has decreased sharply over the period which needs a further detailed investigation.

Attempt is made to identify the regions where maximum decadal variation in SSH has occurred over the country. A decade to decade comparison of mean SSH indicates that the maximum decrease (7%) has taken place from D2 decade to D3 decade which is consistent with the strong decline in solar radiation over India during 1991-2000 reported by Kumari *et al.,* (2007). Spatial patterns of difference of decadal averages of sunshine duration of D3 decade from D2 decade for annual and four seasons brings out regions where the maximum decrease in SSH have occurred Figs. 3 (a-e). These regions are around major urban and industrial centers of India *viz*., Delhi (annual, winter and post monsoon), Jaipur (summer and monsoon), Guwahati (winter), Kolkata (annual and all seasons), Allahabad (summer), Lucknow (winter), Mumbai (annual and summer), Mangalore (annual, summer, monsoon and post monsoon), Pune (winter), Vishakhapatnam (annual and monsoon) and Panjim (summer) where SSH has drastically decreased (-0.5 hours to -1.5 hours per decade). It is a common knowledge that generation and release of anthropogenic pollutants are directly linked with the economic and industrial activities and there is high concentration of aerosol particles in urban centers rather than rural areas. Sarkar *et al.,* (2006) have studied aerosol index over some major Indian cities and have found significant increasing trend in cities located in northern half of India (*viz*., Delhi, Kanpur, Chandigarh, Lucknow, Jaipur, Kolkata and Ahmedabad).

3.1.3. *Temporal variations*

Temporal variations of SSH, CLD and NRD as anomalies from 1971-2000 means for India are shown in Figs. 4(a-e). The most prominent feature of data analysis is that SSH anomalies have become continuously negative since 1990 which is consistent with the significant dimming over India observed by Kumari *et al.,* (2007) who have attributed this decline in solar radiation for 1981-2004 to increase in aerosols due to human activities. A closer look of the all India series of annual pan evaporation (Jaswal *et al.,* 2008) and annual solar radiation (Kumari *et al.,* 2007) suggests a continuous decline even in these two related parameters from 1990 onwards. Large negative anomalies in SSH and simultaneous large positive anomalies in CLD and NRD in the year 1998 (winter and post monsoon) are noteworthy. Annual CLD and NRD anomalies also follow nearly the same pattern having similar inter-annual variations. The drought years of 1972, 1979, 1987 and 2002 are clearly identifiable with relative more sunshine and lesser total cloud and rainy days in annual and monsoon anomalies. The seasonal tendencies in the number of rainy days can be seen especially during monsoon season where a causal relationship between increased (decreased) cloud cover showing increased (decreased) rainy days is very much evident. It is seen from the total cloud amount series that there is no appreciable change in India averaged total cloud cover but the possibilities of trends at regional level can not be ruled out. At the same time, increase in aerosols and other anthropogenic pollutants has been reported by researchers in India (Dey *et al.,* 2004; Singh *et al.,* 2004; Prasad *et al.,* 2004; Ramanathan *et al.,* 2005, Venkataraman *et al.,* 2005 and Sarkar *et al.,* 2006) and in China (Zhang *et al.,* 2004 and Qian *et al.,* 2007). While region specific changes in cloud cover could be one of the factors leading to decline in sunshine, significant increase in aerosols and other anthropogenic pollutants over Indian sub-continent during the last two decades appears to be one of the most important factors in the overall decline of sunshine duration over India.

3.2. *Geographical distribution of annual and seasonal mean sunshine duration*

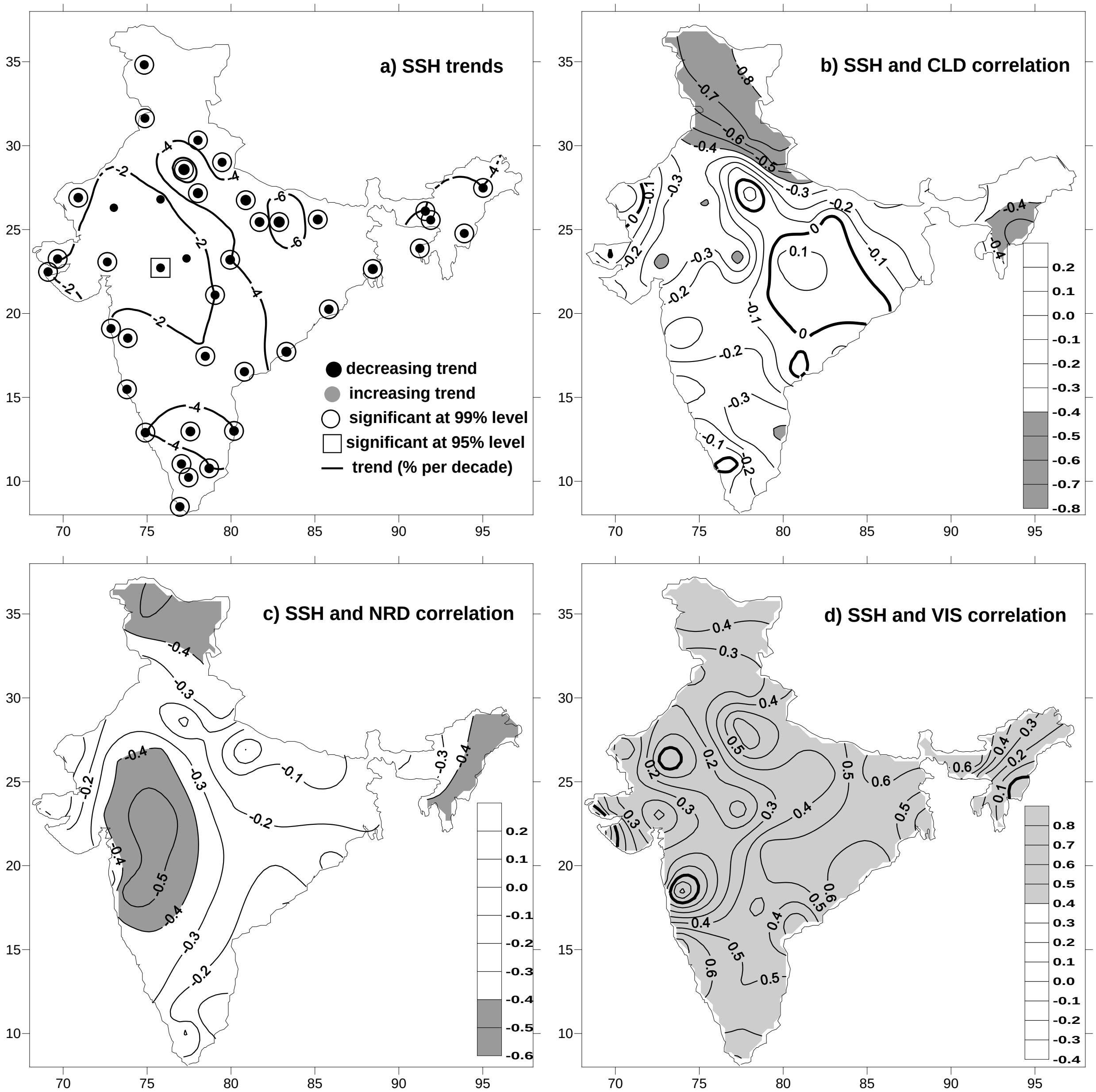
Distribution of sunshine over a place is dependent upon many factors such as surface azimuth, surface tilt angle, solar altitude, solar azimuth, cloudiness, water vapor content, dust, aerosols and atmospheric transparency. Fig. 5 (a) shows the distribution of annual mean SSH which is highest (>8.6 hours/day) over western Rajasthan and adjoining areas in north Gujarat. Regions of least amount of sunshine are over north Kashmir and northeastern states. The inter-annual variability of SSH is maximum (>8%) over Delhi, eastern Uttar Pradesh, Bihar and Gangetic West Bengal as shown by the shaded region. Spatial analysis of winter mean SSH shows regions of highest sunshine (>9.4 hour/day) over Gujarat and western Maharashtra Fig. 5 (b) while north and northeast India are having lowest SSH with maximum CV (>13%). Summer season sunshine is highest (>9.6 hours per day) over Gujarat, southern parts of Rajasthan and adjoining northwest Maharashtra and Madhya Pradesh Fig. 5 (c). The seasonal variability of summer SSH is maximum

TABLE 3

Annual and seasonal sunshine duration trends in hour/decade for all 40 surface observatory stations under study

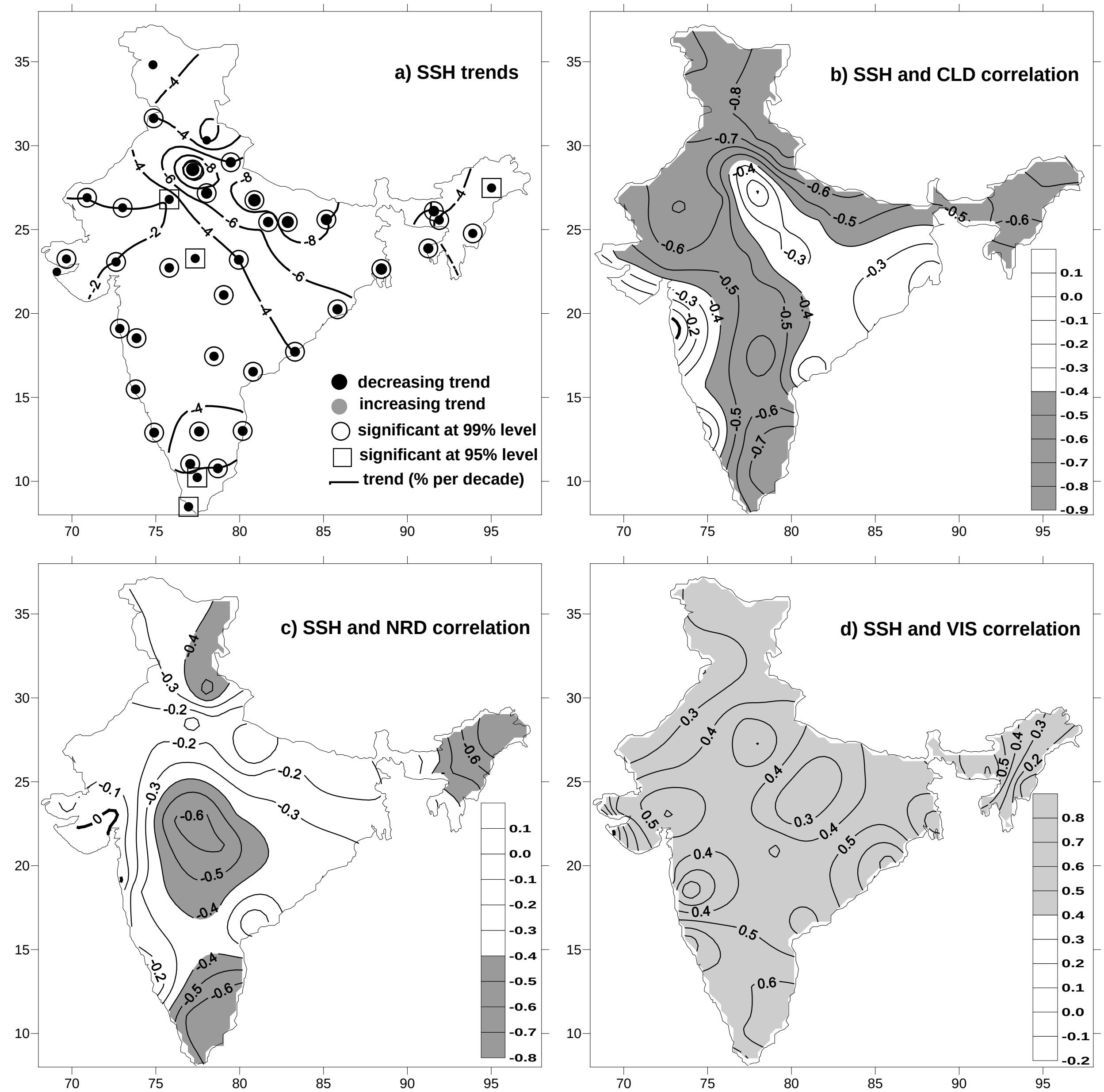
Station	Sunshine duration trends in hour/decade				
	Annual	Winter	Summer	Monsoon	Post monsoon
Srinagar	- 0.18**	- 0.17	- 0.13	- 0.21**	- 0.19*
Amritsar	- 0.16**	- 0.30**	- 0.14*	+ 0.02	- 0.25**
Dehradun	- 0.22**	- 0.05	- 0.25**	- 0.33**	- 0.17*
Pantnagar	- 0.16**	- 0.48**	+ 0.01	- 0.01	- 0.15*
New Delhi	- 0.66**	- 1.10**	- 0.47**	- 0.38**	- 0.93**
Agra	- 0.41**	- 0.64**	- 0.29**	- 0.30**	- 0.42**
Dibrugarh	- 0.22**	- 0.19*	- 0.37**	- 0.15	- 0.18
Jaisalmer	- 0.29**	- 0.19**	- 0.25**	- 0.46**	- 0.21**
Jodhpur	- 0.02	- 0.17**	+ 0.05	+ 0.09	- 0.12
Jaipur	- 0.05	- 0.19*	- 0.11	+ 0.18	- 0.19*
Lucknow	- 0.54**	- 0.94**	- 0.43**	- 0.29**	- 0.64**
Guwahati	- 0.24**	- 0.51**	- 0.26**	- 0.07	- 0.27**
Allahabad	- 0.34**	- 0.48**	- 0.30**	- 0.20*	- 0.42**
Varanasi	- 0.64**	- 0.84**	- 0.67**	- 0.48**	- 0.59**
Patna	- 0.37**	- 0.65**	- 0.20**	- 0.23**	- 0.47**
Shillong	- 0.17**	- 0.24**	- 0.17*	- 0.10	- 0.22**
Imphal	- 0.16**	- 0.21**	- 0.15	- 0.19**	- 0.16*
Bhuj	- 0.20**	- 0.18**	- 0.19**	- 0.23	- 0.18**
Ahmedabad	- 0.14**	- 0.21**	- 0.12*	- 0.11	- 0.11
Bhopal	- 0.03	- 0.19*	+ 0.02	+ 0.07	- 0.17*
Jabalpur	- 0.32**	- 0.37**	- 0.22**	- 0.40**	- 0.27**
Agartala	- 0.21**	- 0.44**	- 0.22**	- 0.02	- 0.20**
Okha	- 0.20**	- 0.08	- 0.30**	- 0.19	- 0.19**
Indore	- 0.12*	- 0.29**	- 0.07	+0.05	- 0.20*
Kolkata	- 0.40**	- 0.70**	- 0.37*	- 0.14	- 0.48**
Nagpur	- 0.16**	- 0.30**	- 0.10	- 0.06	- 0.20**
Bhubaneshwar	- 0.26**	- 0.44**	- 0.17	- 0.14	- 0.33**
Mumbai	- 0.19**	- 0.25**	- 0.09**	- 0.18	- 0.22*
Pune	- 0.24**	- 0.36**	- 0.20**	- 0.19*	- 0.31**
Hyderabad	- 0.18**	- 0.23**	- 0.14**	- 0.14*	- 0.25*
Vishakhapatnam	- 0.42**	- 0.39**	- 0.50**	- 0.37**	- 0.41**
Gannavaram	- 0.22**	- 0.32**	- 0.26**	- 0.12	- 0.20
Panjim	- 0.23**	- 0.29**	- 0.29**	- 0.12	- 0.31**
Chennai	- 0.30**	- 0.37**	- 0.33**	- 0.18**	- 0.40**
Mangalore	- 0.27**	- 0.36**	- 0.36**	- 0.07	- 0.37**
Bangalore	- 0.34**	- 0.41**	- 0.45**	- 0.19*	- 0.40**
Coimbatore	- 0.22**	- 0.40**	- 0.29**	+ 0.04	- 0.42**
Kodaikanal	- 0.16**	- 0.24*	- 0.25**	- 0.05	- 0.26*
Tiruchirapalli	- 0.29**	- 0.35**	- 0.30**	- 0.18*	- 0.49**
Thiruvananthapuram	- 0.23**	- 0.24*	- 0.33**	- 0.15	- 0.28*

* - trends significant at 95% level, ** - trends significant at 99% level



Figs. 6(a-d). Spatial variation of annual (a) sunshine duration (SSH) trend, (b) correlation coefficient of SSH and total cloud amount (CLD), (c) correlation coefficient of SSH and number of rainy days (NRD), (d) correlation coefficient of SSH and good visibility days (VIS). Regions having significant correlation (at 99%) are shaded

(>10%) over Delhi, Jammu and Kashmir and northeast India. Aerosol optical depth over India is significant during summer months (Dey, *et al.*, 2004) and the maximum is observed over the northern parts of the country (Sarkar *et al.*, 2006). Spatial analysis of monsoon SSH [Fig. 5 (d)] shows north and northwest India having higher SSH which is highest (>8.2 hours/day) over western Rajasthan and lowest over coastal Karnataka and northeastern states which are more cloudy due to onset of southwest monsoon. The interannual variability of SSH is maximum (>15%) over eastern Rajasthan which is still hot and dry with frequent occurrence of sand storm/dust storm. Spatial patterns of post monsoon SSH [Fig. 5 (e)] is similar to annual patterns and it is highest (>9.4 hours/day) over western Rajasthan and adjoining areas in north Gujarat which have cloud free skies in this season. South peninsula is having lowest SSH values (<6.2 hours per day) which is under the influence of northeast monsoon. The CV of SSH is highest (>10%) over Delhi and adjoining areas. The geographical distribution of



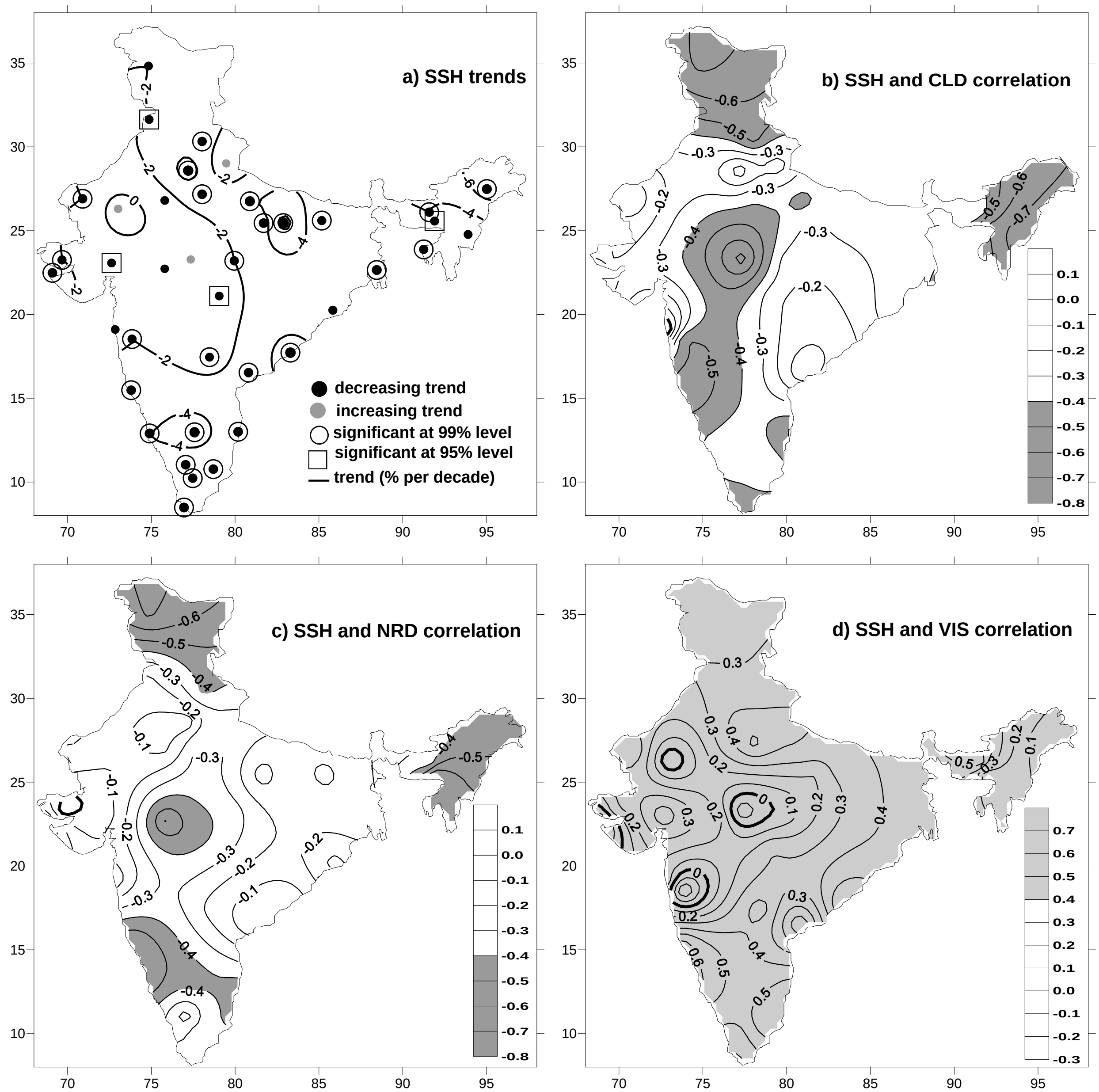
Figs. 7(a-d). Same as in Figs. 6(a-d) but for winter season

sunshine duration indicates west Rajasthan and adjoining north Gujarat as regions of maximum sunlight in India.

3.3. *Spatial patterns of sunshine trends and correlation with other climatic factors*

3.3.1. *Annual*

Annual SSH trends are decreasing for all 40 stations under study (Table 3) and the decreasing trends are significant at 99% for 36 stations. The maximum decline in SSH is along the Indo-Gangetic plains [Fig. 6 (a)]. Regions of highest decrease (>6% per decade) in SSH are over Delhi and eastern Uttar Pradesh while southeast Rajasthan and adjoining northwest Madhya Pradesh is having least decrease. Correlation between SSH and CLD is negative all over the country except over Orissa, Chhattisgarh and Jharkhand as shown in Fig. 6 (b) indicating good relationship over these areas. The spatial analysis of SSH and CLD correlation shows regions of significant negative CC over north and northeast India. Correlation between SSH and NRD is negative all over the country [Fig. 6 (c)] and spatial analysis of CCs shows regions of significant negative correlations over

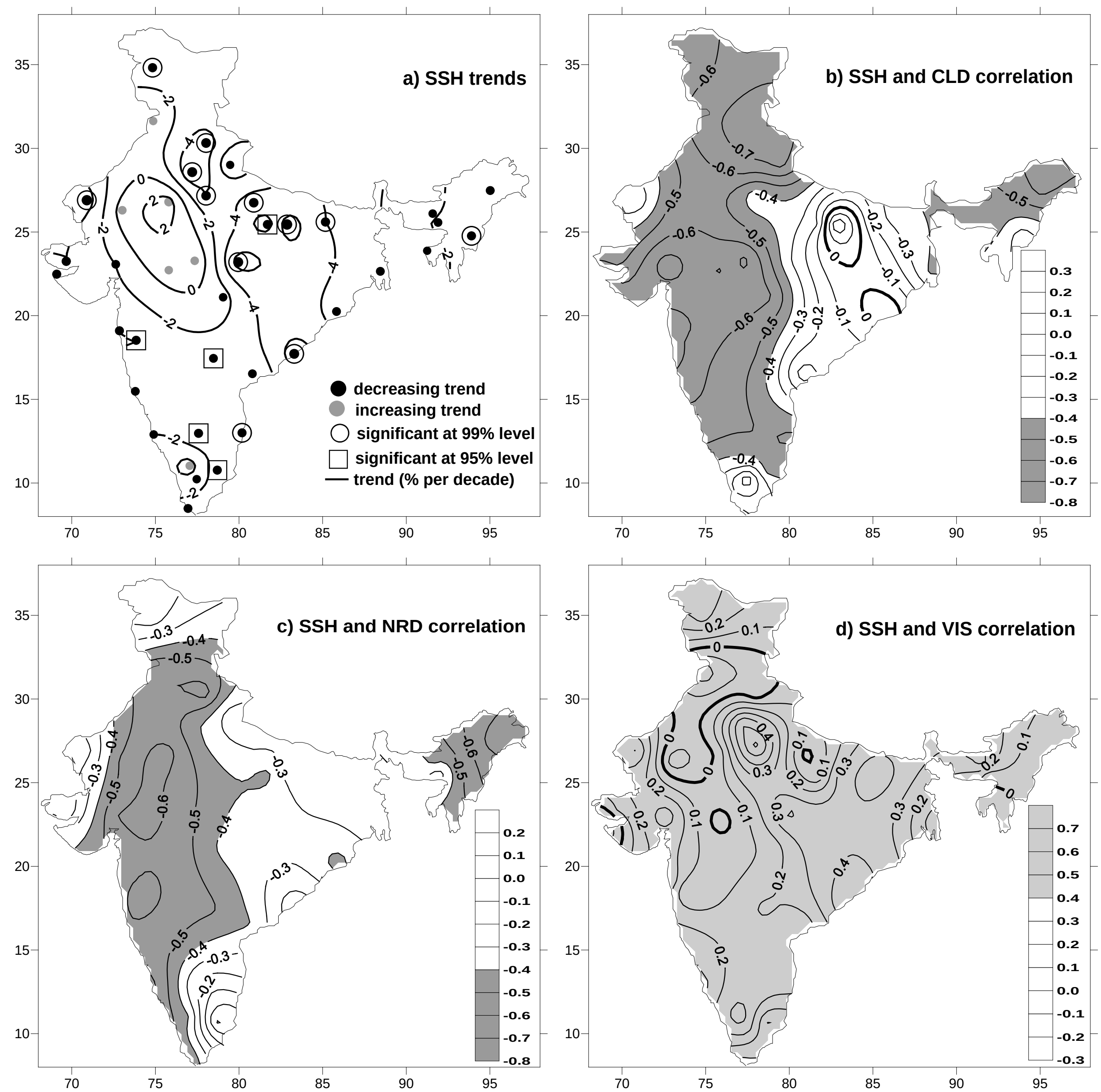


Figs. 8(a-d). Same as in Figs. 6(a-d) but for summer season

Maharashtra and adjoining southwest Madhya Pradesh and Gujarat. Almost all regions of India are having positive correlation between SSH and VIS [Fig. 6 (d)] and considerably large areas over Delhi, Indo-Gangetic plains, Orissa and south peninsula are having significant positive correlations.

3.3.2. *Winter*

Similar to annual trends, SSH trends are decreasing for all stations (Table 3) and the trends are significant at 99% for 32 stations and at 95% for 5 stations. The decreasing trends are stronger over the entire Indo-Gangetic plains as shown in Fig. 7 (a). The maximum decrease in SSH is over Delhi (13% per decade), Lucknow and Varanasi (10% per decade), Patna and Kolkata (8% per decade). Stations in southern peninsula are also showing strong decreasing trends in SSH (Bangalore and Coimbatore 5% per decade, Chennai and Tiruchirapalli 4% per decade). SSH and CLD correlations are significantly negative over north, west, northeast, central and peninsular India [Fig. 7(b)] indicating strong

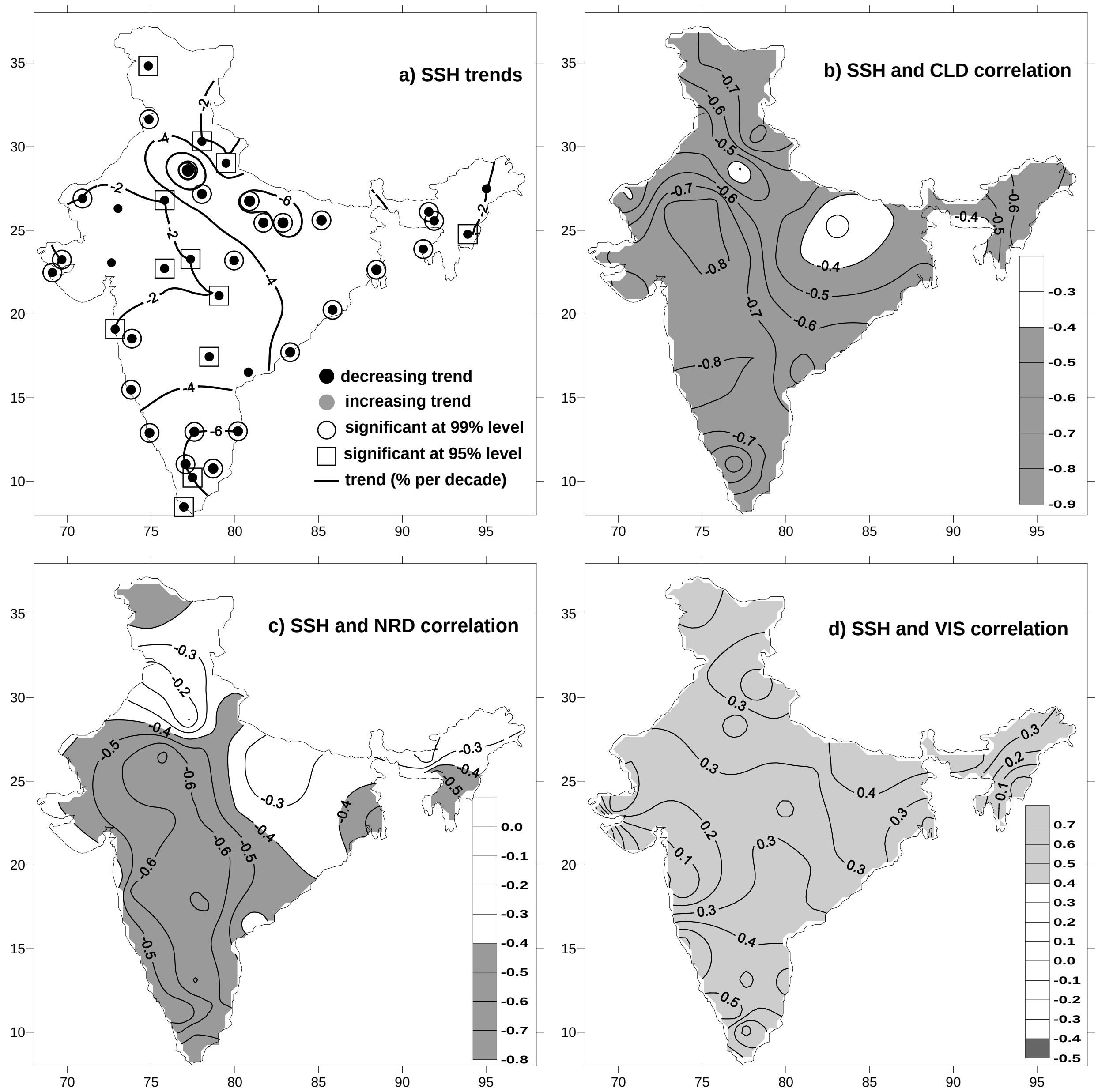


Figs. 9(a-d). Same as in Figs. 6(a-d) but for monsoon season

relationship over these regions during winter season. Fig. 7(c) shows spatial analysis of CCs of SSH and NRD where areas of significant negative CCs are over north Maharashtra, south peninsula and north east India. As expected, SSH is having positive CC with VIS at all stations which mean lesser sunshine during the season is accompanied by lesser number of good visibility days over these areas. Spatial analysis of CCs [Fig. 7(d)] indicates regions of significant CC over Delhi, south peninsula, Orissa and Assam which is possibly due to aerosol loading over these regions. High concentration of aerosols over Indo-Gangetic basin during winter season is reported by Prasad *et al.*, (2004).

3.3.3. *Summer*

Summer season in India is hot and dry and it is characterized by lots of convective activities leading to



Figs. 10(a-d). Same as in Figs. 6(a-d) but for post monsoon season

sand storms/dust storms and thunder storms in many parts of the country. Aerosol loading in the atmosphere is also highest in this season especially in the Indo-Gangetic basin (Sarkar *et al.*, 2006). SSH trends are decreasing for 37 out of 40 stations (Table 3) and the trends are significant at 99% for 27 stations and at 95% level for 4 stations. Fig. 8(a) shows that decreasing trends in SSH are spread all over India and the maximum decrease (>5% per decade) is over Delhi, Varanasi, Dibrugarh and Bangalore. Correlation between SSH and CLD is negative over the entire country [Fig. 8(b)] and the regions of significant negative CC are over north, northeast and central India extending southward up to coastal Karnataka. Correlation between SSH and NRD is also negative over the country [Fig. 8(c)] and regions of significant CCs are over north, northeast and central India and over southwest peninsula where convective rainfall activities are frequent in this season. SSH is having positive correlation with VIS all over the country [Fig. 8(d)] and spatial analysis of CCs shows regions of significant correlation over western Uttar Pradesh, West Bengal, coastal Orissa and south peninsula.

3.3.4. *Monsoon*

Monsoon season SSH trends are decreasing for 34 stations and are increasing for 6 stations as given in Table 3. The decreasing trends are significant at 99% for 12 stations and at 95% level for 5 stations. Fig. 9 (a) shows that the maximum decrease in SSH (>5%) is over Delhi, Uttarakhand, Uttar Pradesh, Bihar and northeastern states. SSH is having small increasing trend over eastern Rajasthan, northwest Madhya Pradesh and north Maharashtra. Correlation of SSH and CLD is negative over the country except over areas extending from east UP to coastal Orissa [Fig. 9 (b)]. CCs of SSH and CLD are significantly negative over northeast India and western half of India west of 80°E which means that a sunny monsoon season over the region is accompanied by lesser cloudiness. Spatial analysis of CCs of SSH and NRD over India [Fig. 9(c)] is similar to CCs of SSH and CLD patterns indicating strong positive relationship between these two parameters in this season. Even though SSH is having positive correlation with VIS [Fig. 9 (d)], the magnitudes of CCs are not significant over the country owing to increase in atmospheric transparency during this season. The spatial analysis of CCs of SSH and VIS indicates role of strong monsoon winds and rainfall in dispersing and washing down the pollutants and thus increasing atmospheric transparency.

3.3.5. *Post monsoon*

Post monsoon SSH trends are decreasing for all stations (Table 3) and the decreasing trends are significant at 99% for 24 stations and at 95% for 12 stations. The maximum decrease in SSH (>5% per decade) is along the Indo-Gangetic plains and over south peninsula [Fig. 10 (a)]. Regions over Gujarat, south Rajasthan, west Madhya Pradesh and north Maharashtra are having least decrease (<2% per decade). Spatial patterns of CCs of SSH and CLD are shown in Fig. 10 (b) where all regions of the country (except Bihar) are having significant negative CCs. This means that a sunny post monsoon season is accompanied by lesser cloudiness and *vice versa*. Spatial analysis of CCs of SSH and NRD [Fig. 10 (c)] shows regions of significant negative CCs over west Madhya Pradesh, east Rajasthan, east Gujarat, Maharashtra and entire south peninsula. Fig. 10(d) shows spatial analysis of CCs of SSH and VIS where region of significant positive CC are over north Bihar and south peninsula indicating the influence of southwest monsoon in washing down pollutants over large parts of the country and increasing the atmospheric transmissivity.

The data analyses based upon 40 stations for the period 1970-2006 show that all India SSH and VIS have decreased by 3% and 21% per decade respectively but there is almost no change in CLD and NRD due to large spatial and temporal variations in these two parameters. More than 90% stations are showing significant decrease in sunshine duration for annual, winter and post monsoon while monsoon season is having least number of stations (43%) with significant decrease as summarized in Table 3. Spatially highest decrease in sunshine hours has occurred in Indo-Gangetic plains and south peninsula while regions over Rajasthan and Gujarat have lowest decrease. Out of 40 stations under study, the maximum decrease in SSH has occurred at New Delhi (annual, winter and post monsoon at -0.66, -1.10, -0.93 hours per decade respectively) followed by Varanasi (summer and monsoon at -0.67, -0.48 hours per decade respectively).

Correlation analysis of SSH with CLD, NRD and VIS shows interesting results. Stations showing maximum decrease in SSH are having lower negative correlation with CLD and NRD indicating lesser influence of these parameters at those stations. The same stations are having higher positive correlation with VIS indicating a strong relationship with SSH. A comparison of SSH correlations with CLD, NRD and VIS [Figs. (6-10)] clearly shows regional and seasonal variations in factors contributing to overall decrease in sunshine duration over the country. Sunshine duration and daytime total cloud cover are significantly correlated over large regions during winter (north, northeast, west and central India and south peninsula), monsoon (west of 80° E and northeast India) and post monsoon seasons (entire country except east Uttar Pradesh and Bihar) suggesting a major influence on sunshine variation, although other factors such as atmospheric turbidity may also play a part in explaining long term trends. Similarly, large parts of India have significant SSH and VIS correlations during winter (west Uttar Pradesh, Haryana, Delhi, east Rajasthan, Gujarat, Bihar, Jharkhand, Orissa and extreme south peninsula) and summer (west Uttar Pradesh, Bihar, West Bengal, Orissa and south peninsula) which suggest that, although atmospheric transparency has a major influence on sunshine variation, other factors such as cloud cover may also play a part over those areas. Even though there are reports of decrease in total cloud cover over India (Rao *et al.*, 2004 and Warren *et al.*, 2007), a comprehensive analysis of long term trends in cloud cover and cloud types is needed.

The special geographical features of the Indian sub-continent affect local climate and its variability over India with respect to changes in global climate. The high Himalayan ranges and the Indo-Gangetic plains in the North, the Arabian Sea and the Bay of Bengal in the South and the Thar desert in the west are some of natural contributors to climate variability over India. In addition to these, other factors like dust from deserts, greenhouse gases, anthropogenic aerosols, large-scale wood/charcoal burning, changes in land use pattern, increased fossil-fuel combustion and large scale urbanization are also affecting the climate over India. According to Dey *et al.,* (2004) and El-Askary *et al.,* (2006) large amount of dust particles are transported to Indo-Gangetic plains from the Thar and Middle East deserts by the westerly winds (particularly in hot weather season). The further movement of these dust particles is blocked by higher Himalayan mountain ranges which act as a natural barrier and the dust getting accumulated over the Indo-Gangetic basin. Sarkar *et al.,* (2006) have concluded that aerosol loading over the major cities in India has increased significantly in recent years. Aerosol optical depth over India is significant during summer months (Dey, *et al.,* 2004) and the maximum is observed over the northern parts of India (Sarkar *et al.,* 2006) which is attributed to the bio-fuel used for cooking and other anthropogenic activities by Singh *et al.,* (2004). Several recent studies (Stanhill and Kalma, 1995; Yu *et al.,* 2001; Kaiser and Qian, 2002; Liu *et al.,* 2002; Liang and Xia, 2005; Qian *et al.,* 2006 & 2007 and Stanhill and Cohen, 2008) have attributed decrease in sunshine duration to increase in aerosol loading. It is widely believed by researchers that tiny particles of soot or chemical compounds like sulphates reflect sunlight and they also promote formation of bigger, long lasting clouds.

Global ‘dimming’ and ‘brightening’ is currently an active area of research in climate change studies. Although the cause of the decrease in solar radiation (sunshine duration) is still not fully known, the most accepted reason at present is a change in the transmissivity of the Earth’s atmosphere owing to an increase in aerosol concentrations as a consequence of anthropogenic emissions (Stanhill, 2005). Emissions of aerosol precursors in South Asia have increased about six times since 1930 (Ramanthan *et al.,* 2005) and atmospheric visual range has correspondingly decreased (Kaiser and Qian, 2002). Horizontal surface visibility has deteriorated sharply over India (De *et al.,* 2001) and the trends are similar to the observed trends over China as reported by Liang and Xia (2005). In addition to decrease in sunshine duration over India, solar radiation (Kumari *et al.,* 2007) and pan evaporation (Jaswal *et al.,* 2008) has also decreased and Ramanathan *et al.,* (2005) have attributed decline in evaporation (simulated) world over to increase in aerosol concentration. Combined with evidence of changes in total cloud cover and increased aerosol optical depth over India, the causes of decline in sunshine duration appear to be changes in anthropogenic aerosols, cloud cover and/or cloud properties and potential interactions between them. However the impacts of anthropogenic aerosols on cloud albedo and cloud amount at large spatial scales and over long time periods remain uncertain.

4. Conclusions

Sunshine duration trends and correlations with other climatic factors were analyzed for 40 stations in India for 1970-2006. Most of the decline in sunshine duration has occurred 1990 onwards when anthropogenic aerosols increased over the Indian sub-continent as reported by several investigators. Based upon trend and correlation analysis of sunshine duration and other related parameters, following conclusions are drawn:

(*i*) Geographical distribution of mean sunshine duration suggests west Rajasthan and adjoining Gujarat as ideal locations for harnessing solar energy where climatologically more than 3100 hours of annual total sunshine duration is assured.

(*ii*) Sunshine duration over India has decreased for all months and the decreasing trends are significant at 99% for January to May and October to December. Maximum decrease in sunshine duration has occurred in January (-0.44 hours/decade) followed by December (-0.39 hours/decade) and November (-0.32 hours/decade). Spatial analysis of sunshine duration trends identifies Indo-Gangetic plains, west coast and south peninsula as the regions where maximum decrease has occurred.

(*iii*) The maximum decrease in sunshine duration has occurred at New Delhi (annual at 8% per decade, winter at 13% per decade and post monsoon at 10% per decade) and Varanasi (summer and monsoon seasons at 7% per decade). Spatial analyses indicate regions having maximum decrease in sunshine duration have less than average mean sunshine duration for the season with higher coefficient of variation.

(*iv*) Averaged India sunshine duration is having weak negative correlation with total cloud amount and rainy days for annual and four seasons. However, during winter, monsoon and post monsoon seasons, large parts of the country over north, northeast and south peninsula are having significant negative correlation between sunshine duration and total cloud amount (rainy days). Sunshine duration is having significant positive correlation with good visibility days over many parts of India especially over north, northeast, east coast and south peninsula during winter, summer and post monsoon seasons suggesting strong relationship over those areas. Thus the correlation analysis indicates regional and seasonal variations in factors explaining the long term trends in sunshine duration.

Solar radiation (sunshine duration) has profound influence on surface temperature, evaporation, the hydrologic cycle and ecosystems and it is the primary source of energy required for sustenance of life on this planet. A detailed analysis of cloud amount, cloud types and visibility trends is required in future studies to address the issues related to decline of sunshine duration over India.

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