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Understanding the climatology and long-term trends in solar radiation using ground based *in-situ* observations in India

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सार – बिजली उत्पादन में सौर ऊर्जा के इष्टतम उपयोग के लिए देश भर में सौर ऊर्जा क्षमता की विविधता को समझना आवश्यक है, जिसके लिए सौर विकिरण और इसकी विविधताओं की सटीक जानकारी की आवश्यकता होती है। वर्तमान अध्ययन में, हम 1985-2019 की अवधि के लिए भारत मौसम विज्ञान विभाग से प्राप्त इन-सीटू डेटा का उपयोग करके वैश्विक विकिरण (GR), विकीर्ण विकिरण (DR), उज्ज्वल धूप घंटे (BHS) और सौर ऊर्जा की तकनीकी क्षमता (सौर फोटोवोल्टिक क्षमता; SPV क्षमता) की जलवायु विज्ञान और प्रवृत्तियों की जांच करते हैं। GR उत्तर-पश्चिम और प्रायद्वीपीय (सुदूर उत्तर और उत्तर-पूर्व) भारत के अंतर्देशीय क्षेत्रों में उच्च (निम्न) है, जबकि DR तटीय स्टेशनों (देश के सुदूर उत्तरी भागों) पर उच्च (निम्न) है। उत्तर-पश्चिम (उत्तर, उत्तर-पूर्व और दक्षिणी प्रायद्वीपीय) भारत में BHS अधिक (कम) है। देश में पर्याप्त क्षेत्रीय विविधताओं के साथ 1800-3400 Wm^{-2} की रेंज में SPV क्षमता है। उत्तर-पश्चिमी क्षेत्रों (उत्तर, उत्तर-पूर्व और दक्षिणी प्रायद्वीपीय भारत) में उच्च (निम्न) SPV क्षमता देखी गई। देश के अधिकांश हिस्सों में GR और BHS (DR) में महत्वपूर्ण कमी (वृद्धि) की प्रवृत्ति है। हालाँकि, हाल के दशक में GR (DR) के कमी(वृद्धि) की दर क्षीण (प्रबल) हुई है। अधिकांश चयनित स्टेशनों में सौर ऊर्जा की तकनीकी क्षमता में उल्लेखनीय गिरावट देखी जा रही है जो चिंताजनक है। सौर संसाधनों से ऊर्जा आवश्यकताओं को पूरा करने के लिए बेहतर दक्षता वाले सौर पैनलों के व्यापक उपयोग की आवश्यकता है।

ABSTRACT. Understanding the variations of solar power potential over the country is essential for the optimum utilisation of solar energy in power generation, which demands accurate information of solar radiation and its variations. In the present study, we investigate the climatology and trends of global radiation (GR), diffuse radiation (DR), bright sunshine hours (BHS) and technical potential of solar power (Solar Photovoltaic potential; SPV potential) using in-situ data procured from India Meteorological Department for the period 1985-2019. GR is high (low) over the northwest and inland areas of peninsular (extreme north and northeast) India, whereas DR is high (low) over the coastal stations (extreme northern parts of the country). BHS is more (less) over northwest (north, northeast and southern peninsular) India. The country has SPV potential in the range of 1800-3400 Wm^{-2} with substantial regional variations. High (low) SPV potential is observed in the northwest regions (north, northeast and southern peninsular India). The GR and BHS (DR) have (has) a significant decreasing (increasing) trend in most parts of the country. However, the rate of decreasing (increasing) of GR (DR) has been weakened (strengthened) in the recent decade. The technical potential of solar power has a significant decreasing trend in most of the selected stations which is alarming. It necessitates the wide use of solar panels with better efficiency to meet the energy requirements from solar resources.

Key words – Solar radiation, In-situ observations, Technical potential of solar power, Trend analysis

1. Introduction

Solar radiation has an important role in governing the earth's surface-atmosphere energy exchange and the climate of the earth (Ackerman *et al*., 2000). It modulates global energy balance and changes the climate and hydrological cycle (Budyko 1969; Liepert *et al*., 2004; Pfeifroth *et al*., 2018; Obryk *et al*., 2018). Various sectors of the society such as agriculture, energy, economy, *etc*. directly or indirectly depend on the incoming solar radiation (Greenwald *et al*., 2006; Gupta *et al*., 2017; Raina and Sinha, 2019). Long-term variations in the global solar radiation at the surface showed a general decreasing trend over many parts of the world from 1950s to 1980s, followed by an increase, which are often termed as global dimming and global brightening, respectively

(Ohmura and Lang, 1989; Russak, 1990; Stanhill and Cohen, 2001; Liepert, 2002; Liu *et al*., 2004; Wild *et al*., 2005; Wild 2009; Gilgen *et al*., 2009; Wild, 2012; Pfeifroth *et al*., 2018). The global dimming before the 1980s was mainly due to the negative trends in Asia and North America, and the global brightening after 1980s was mainly contributed by Europe and Oceania (Yuan *et al*., 2021). The change in the pattern of emission of anthropogenic aerosols in the atmosphere is considered to be the primary reason for these changes (Streets *et al*., 2006). According to IPCC AR6 (Intergovernmental Panel on Climate Change Assessment Report 6), multidecadal dimming and brightening trends in incoming solar radiation at Earth's surface occurred at various locations all over the world. Multidecadal variations in anthropogenic aerosol emissions are thought to be a major contributor; although, multidecadal variability in cloudiness also played a significant role (Arias *et al*., 2021).

Despite of the global brightening trend after 1980s, dimming trend continued in India (Wild *et al*., 2005; Ramanathan *et al*., 2005; Padmakumari *et al*., 2007); a decrease in global solar radiation by 0.89 Wm^{-2} was observed during 1981-2006. The decreasing trend was of the order of 0.6 Wm^{-2} $year^{-1}$ for the period 1971-2000 and 0.2 Wm^{-2} $year^{-1}$ for the period 2001-2010 (Padmakumari *et al*., 2017). Aerosols and clouds are found to be the important factors responsible for the changes in the solar radiation reaching the surface (Padmakumari *et al*., 2007; Padmakumari and Goswami, 2010; Soni *et al*., 2012; Latha *et al*., 2014; Soni *et al*., 2016). Further, the rate of dimming during the cloudy conditions (12Wm^{-2} $decade^{-1}$) was found to be twice compared the clear sky conditions, indicating a larger role of clouds in the solar dimming (Padmakumari and Goswami, 2010). However, a reversal in the trend of global radiation was observed at some stations after 2001 (Soni *et al*., 2016). They found that the declining trend of global radiation over India as a whole has been reduced from 0.6 Wm^{-2} $year^{-1}$ to 0.2 Wm^{-2} $year^{-1}$ from the period 1971-2000 to 2001-2010, and the reversal is more evident in clear sky conditions. The study also highlighted the regional variations in the trends, which is one of the objectives of the present study.

Diffuse radiation is the amount of solar radiation scattered by atmospheric particles. Clear sky transmits a large percentage of solar radiation and therefore exhibits relatively small diffuse radiation whereas a partly cloudy or turbid atmosphere exhibits high diffuse radiation. Studies on long term variability of diffuse radiation are less compared to global radiation, mainly due to scarcity of data. Although, several studies illustrated an increase in diffuse radiation during the dimming period and a decreasing trend during brightening period in the last few decades over Europe, United States, China, South Africa and India (Russak, 1990; Liepert and Tegen, 2002; Zhang *et al*., 2004; Power and Mills, 2005; Liang and Xia, 2005; Abakumova *et al*., 2008; Mercado *et al*., 2009; Soni *et al*., 2012; Sanchez-Lorenzo *et al*., 2013). A decrease in diffuse radiation is observed in Germany and Ireland, whereas no significant trend from 1960 to 1990 and a significant decreasing trend after 1980 are observed in China (Liepert, 1997; Stanhill, 1998; Liang and Xia, 2005). Soni *et al*. (2012) studied the long term variability and trends of diffuse radiation for the period 1971-2005 using the data of twelve stations. They observed a significant increasing trend in the diffuse radiation at four stations in all sky conditions and an increasing trend at seven stations during clear sky conditions. However, Soni *et al*., (2016) observed a less pronounced trend and more complex spatial pattern in the diffuse radiation over India for 1971-2010.

Solar energy has been recognized as an alternative to the conventional energy resources. Amongst all the clean technologies, solar energy serves as an effective renewable energy resource to mitigate greenhouse gas emissions and reduce global warming (Ramachandra and Krishnadas, 2011). Further, solar energy is one of the resources that are capable of self-reliant energy generation, reducing foreign energy dependence (IPCC, 2011). In tropical countries like India, solar energy has immense potential (Muneer *et al*., 2005; Ramachandra and Krishnadas, 2011). The energy of about 5,000 trillion kWh per year is incident over India's land area with most parts receiving 4-7 kWh m^{-2} per day. India has already identified its potential and become one of the forerunners in the renewable energy markets around the world. Indian Solar Photovoltaic Program was launched in the early 1980s, and the initial target of 20GW solar capacities by 2022 was surpassed by a capacity addition of 28.18 GW in 2019 under Jawaharlal Nehru National Solar Mission program (Ministry of New and Renewable Energy, 2019). India's Intended Nationally Determined Contributions (INDCs) target is to achieve about 40 percent cumulative electric power installed capacity from renewable energy resources and to reduce the emission intensity of its GDP by 33 to 35 percent from the 2005 level by 2030.

The solar energy resource can be defined based on different types of potentials such as theoretical potential, geographical potential, technical potential and economical potential (Wijk and Coelingh, 1993):

(*i*) *Theoretical potential* : It is the theoretical limit of the solar energy that can be converted to electric power.

(*ii*) *Geographic potential* : It is defined as the theoretical potential reduced by the energy generated at areas that are considered available and suitable for the energy production.

(*iv*) *Technical potential* : It is defined as the total geographical potential that can be converted to electrical energy using photovoltaic (PV) systems, considering the efficiency and other technical constraints of the PV systems. The technical potential is also called as Solar Photovoltaic (SPV) potential.

(*v*) *Economical potential* : It is the total technical potential that can be generated at costs that are competitive with alternative energy resources.

Since the development cost of solar energy is higher, economic feasibility is very important for implementing regional solar energy projects. Several regional studies assessed the economic feasibility of solar projects over many parts of the world (Janke, 2010; Kabir *et al*., 2010; Charabi and Gastli, 2011; Gürtürk, 2019; Abas *et al*., 2022). In the context of India, a few studies reported the geographical potential as well as the technical potential of solar energy in India using satellite data (Ramachandra *et al*., 2011; Mahtta *et al*., 2014; Kalita*et al*., 2019; Mishra *et al*., 2020). Ramachandra *et al*. (2011) observed that nearly 58% of the geographical area of India including the Gangetic plains (Trans, middle and upper), Plateau regions (central, western and southern), western dry region, Gujarat plains and hill regions as well as the west coast regions including the Ghats have annual average insolation of more than 5kWh/m^2/day, where the potential for producing solar energy is high. Mahtta *et al*., (2014) mapped the district-wise potential for concentrating solar power (CSP) and centralized solar photovoltaic (SPV) technology based power plants in India. Mishra *et al*., (2020) assessed the solar power potential of the rooftop areas of Uttarakhand using satellite imageries. Kalita *et al*., (2019) showed that northeast India also has a vast potential of solar energy and it can be harvested economically.

A recent study by Anandh *et al*. (2022) found that solar energy potential over the Indian landmass is expected to reduce due to climate change, which is in fact would be a concern for the production of energy from renewable energy resources. They indicated the necessity of an expanded and more efficient solar energy network in the future. Research to find out highly efficient and low-cost solar power technologies is being done throughout the world (Panwar *et al*., 2011). Although, in order to make the best use of these technologies, it is important to know the actual solar power potential on the ground (Viana *et al*., 2011). Therefore, the present study aimed to understand the climatology of global, diffuse radiations, bright sunshine hours and the SPV potential over different stations and their changes during the past 3 decades. Section 2 depicts the Data and Methodology utilized for the study, Section 3 discusses the results and the important findings are summarised in Section 4.

2. Data and methodology

India Meteorological Department (IMD) has a network of radiation observations covering 45 stations across India (as on December 2022). Global solar radiation, diffuse solar radiation and bright sunshine durations are the basic parameters observed at all these stations. The global solar radiation is observed using Class One or Class Two pyranometers and the diffuse radiation is observed using pyranometers with a shading ring. The pyranometers operate in the wavelength range 285-4000 nm and meets the World Meteorological Organisation (WMO) requirements (WMO, 1983). Bright sunshine duration provides the amount of time when the solar radiation exceeds a specific threshold, which is observed by Campbell Stokes sunshine recorders. The instruments are regularly monitored and maintained by the Radiation Laboratory of India Meteorological Department at Pune, which serves as the National Radiation Centre for India as well as the Regional Centre of WMO for Asia. The Radiation Laboratory maintains a set of reference and standard instruments to ensure the accuracy of radiation instruments in India and also in the regional scale. The standards at the Radiation laboratory are periodically compared with the international standards at World Radiation Centre at Davos, Switzerland. The reference standards are periodically checked with the reference standards at Pune which are used to calibrate the new instruments and also the instruments at the stations. Accuracy of the standard instrument is about ±0.3%, and accuracy of instruments in the network is about ±2%. More details on the radiation instruments are provided in Soni *et al*. (2012). Data from all the radiation stations are collected at IMD Pune, undergo quality control checks recommended by the WMO and archived.

14 radiation stations in India have been recognized as World Radiation Data Centre stations (WRDC). WRDC collects, archives and publishes the data for the world, to ensure the availability of these data for research purposes by the international scientific community. The data from these stations are being shared internationally and published in the bulletin "Solar Radiation and Radiation Balance Data. The World Network". The present study uses data from both WRDC recognized stations as well as the other stations (Non WRDC).

In the first stage, we identified the stations with continuous long-term data and the time period with the maximum data availability (1985-2019). Stations with a

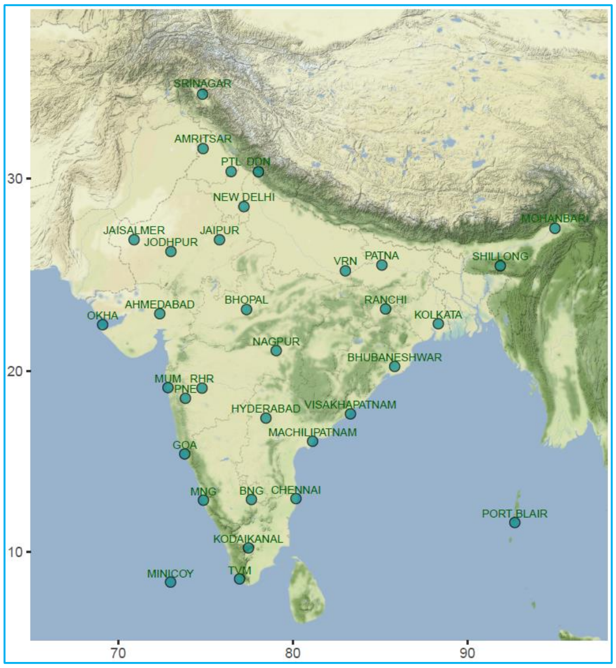


Fig. 1. Location map of radiation stations used for the study

minimum of 20 years data during the study period have been selected for the preparation of climatology. Accordingly, 33 (32) stations have been used to study the monthly and regional variations of global solar radiation (bright sunshine hours and SPV potential) and 22 stations have been used to study the diffuse radiation. The locations of the stations are provided in Fig. 1. The stations that have missing data of continuous 5 years (or more) are not considered for the trend analysis. Therefore, 13 (11) stations with continuous data during 1985-2019 have been selected for the trend analysis of global radiation and diffuse radiation (bright sunshine hours and SPV potential).

The SPV potential of electricity generation is computed using the formula provided in Hoogwijk (2004). According to their study, the technical potential (E_i) at a point 'i' is given by,

$$E_i = G_i \times \eta_m \times P_r \quad (1)$$

where G_i is the geographic potential, $G_i = A_i \times h \times I$, I is the global insolation in kWh/m^2/day, A_i is the suitable area for PV installation, h is the number of sunshine hours in a day, η_m is the conversion efficiency for PV modules which depends on the type of PV cells and module temperature and P_r is the performance ratio of the PV system. Since we used point data from stations that records the radiation per unit area, A_i is taken as 1. The performance ratio is the ratio of on field performance of the system to its performance at standard test conditions of 1000 M/m^2 global insolation, 25 °C module temperature and 1.5 air mass (Ramachandra *et al*., 2011). The efficiency of commercially available crystalline silicon modules has increased in the last decades to 12-16% (Oliver and Jackson, 2000; Turkenburg, 2000). We have taken the value of conversion efficiency as 12%, and the performance ratio as 0.6 in this study (Mahtta *et al*., 2014).

The monthly mean and annual mean of all the parameters such as global radiation, diffuse radiation, bright sunshine hours and SPV potential are investigated and the regional variations are quantified. Seasonal variations are also discussed on the basis of monthly variations. For this, seasons are classified as per the definition of the India Meteorological Department; *i.e*. winter (Jan-Feb), Pre-monsoon (Mar-May), Monsoon (Jun-Sep) and post monsoon (Oct-Dec). Further, trends of global radiation, diffuse radiation, bright sunshine hours and SPV potential for all months and on annual basis are also investigated and significant trends at 0.05 level are identified using *student's t-test*. The significance of the trend is further confirmed using the non-parametric Mann Kendall test (Mann, 1945; Kendall, 1975).

3. Results and discussions

3.1. *Monthly climatology of global radiation*

Global solar radiation (GR) is the total amount of solar radiation that is being received per unit area on the earth surface. Climatological monthly mean of GR for the period 1985-2019 is given in Fig. 2 and Table 1. It shows a substantial month to month variations over all the stations which can be attributed to the apparent movement of the sun and local climatology.

An increase in GR from north to south is evident during the winter months with minimum GR over Srinagar (108.86 Wm^{-2}) and Amritsar (143.11 Wm^{-2}) in January and February, respectively, and maximum over Bengaluru in both months (236.62 Wm^{-2} and 264.08 Wm^{-2} in January and February, respectively). This regional variation is in line with the apparent position of the sun during the season. Interestingly, the high-altitude stations such as Kodaikanal (232.99 Wm^{-2} and 250.3 Wm^{-2} in January and February, respectively) and Bengaluru exhibit high GR than that of other stations which can be attributed to less attenuation of radiation in the atmosphere at high altitudes. It must be noted that, in addition to the high-altitude stations of peninsular India, Okha station also exhibits high GR (252.45 Wm^{-2}) during February. Overall, the stations such as Goa, Thiruvananthapuram,

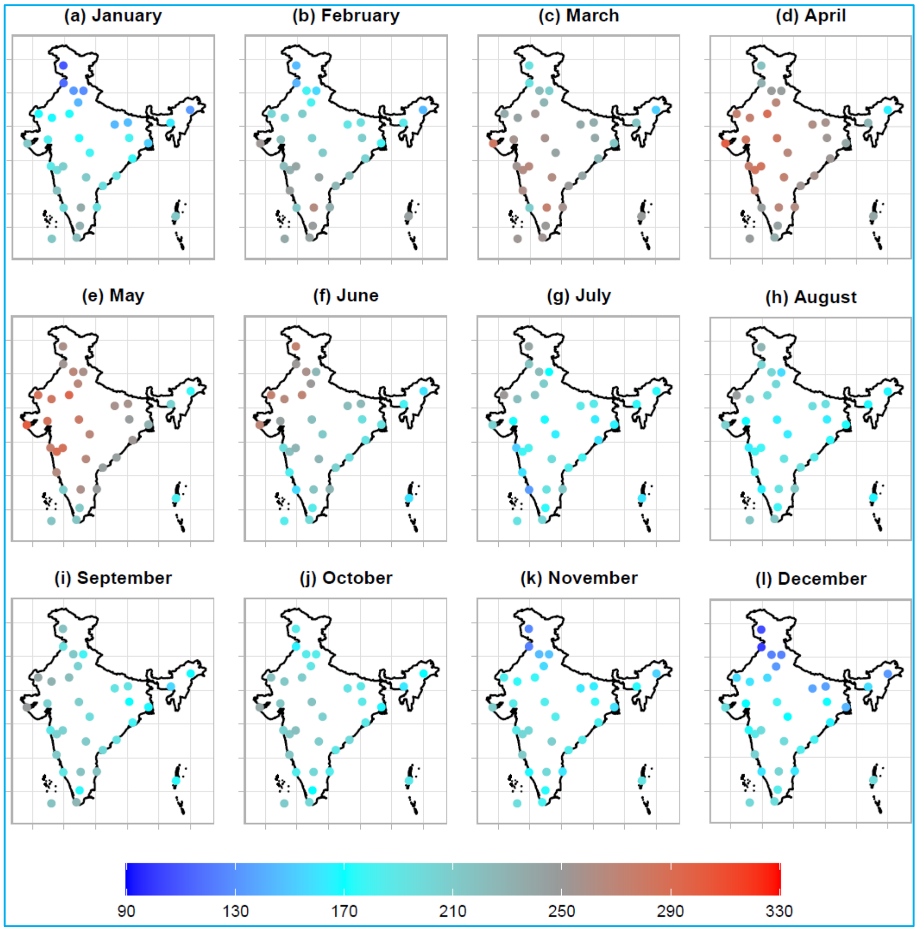


Fig. 2. Monthly mean of global radiation (Wm^{-2}) during the period 1985-2019

Kodaikanal, Port Blair and Bengaluru have high GR (>210 Wm^{-2}) during the season whereas the stations such as Srinagar, Amritsar, Dehradun and Mohanbari have low GR (<160 Wm^{-2}).

GR follows the apparent movement of the sun towards north during the pre-monsoon season, and high values are observed mainly over peninsular regions, central and northwest regions and north and northwest regions in March, April and May, respectively. Minimum (maximum) GR during the season is observed in Mohanbari (Okha) with values 152.97 Wm^{-2} (281.89 Wm^{-2}), 165.27 Wm^{-2} (300.19 Wm^{-2}) and 175.60 Wm^{-2} (301.82 Wm^{-2}) in March, April and May, respectively. It is observed that Mohanbari, Mangalore, Kolkata and Shillong (Ahmedabad and Bhopal) exhibit low (high) GR throughout the season.

Monsoon clouds reduce the GR over most parts of India. Jaisalmer receives the maximum GR during June-August (274.06 Wm^{-2},251.29 Wm^{-2} and 247.08 Wm^{-2} in June, July and August, respectively) and Okha receives the maximum GR in September (248.26 Wm^{-2}). It is minimum in Mangalore, Dehradun and Shillong during June-July (157.39 Wm^{-2}, 133.59 Wm^{-2}, respectively), August (157.09 Wm^{-2}) and September (155.3 Wm^{-2}), respectively. Low values of GR indicate enhanced cloudiness over these stations. The GR is very low over the west coast and northeast regions during June-July, northeast and some stations in north and central India in August and northeast in September months. While, high GR is confined over northwest India due to less cloudiness over the region.

The apparent movement of the sun to the southern hemisphere leads to a reduction in global radiation over India during the post monsoon season. High GR is observed over central and northwest India in October, which shifts to northwest and northern peninsular regions in November and peninsular India and island regions in December. An increase in GR from north to south is evident during November-December months. Maximum GR during the season is observed in Okha (238.03 Wm^{-2} in October) and Goa (210.83 Wm^{-2} and 204.69 Wm^{-2} in

TABLE 1

Monthly mean of global radiation during the period 1985-2019

S. No.	Station	Global radiation (Wm^{-2})												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1.	Ahmedabad	182.48	219.18	255.66	283.01	285.42	243.30	171.09	169.12	206.28	213.64	185.50	170.15	215.22
2.	Amritsar	115.36	143.11	192.76	232.92	253.16	251.34	215.45	202.84	192.71	165.85	123.20	100.94	182.60
3.	Bengaluru	236.62	264.09	274.64	267.84	259.13	216.02	192.63	192.76	216.63	200.11	199.51	203.35	226.66
4.	Bhopal	172.57	207.16	256.85	281.89	278.70	220.51	168.60	163.95	208.62	217.30	183.26	179.10	211.45
5.	Bhubaneshwar	175.26	204.48	226.14	252.22	252.28	192.37	160.63	174.71	179.14	187.06	180.31	166.00	195.76
6.	Chennai	194.04	234.07	256.73	263.32	248.31	227.61	212.41	212.61	217.17	183.43	160.81	161.56	214.15
7.	Dehradun	128.24	156.61	207.86	246.64	258.90	226.24	169.90	157.10	178.52	184.10	148.53	124.57	182.28
8.	Goa	218.42	246.41	259.91	270.42	263.84	182.05	159.93	182.91	211.16	214.72	210.83	204.70	218.55
9.	Hyderabad	211.56	242.07	261.96	272.79	265.79	227.56	196.81	191.30	211.45	209.86	207.77	198.19	224.56
10.	Jaipur	171.88	209.63	254.50	288.79	294.30	270.98	217.62	198.99	221.33	209.37	176.42	156.40	222.44
11.	Jaisalmer	168.38	201.70	236.41	273.46	286.40	274.07	251.30	247.08	239.57	218.37	183.09	157.14	228.14
12.	Jodhpur	168.32	205.20	242.74	274.29	282.15	265.65	220.15	206.65	230.19	212.97	174.60	160.70	220.25
13.	Kodaikanal	232.99	247.47	250.30	242.94	212.94	185.26	174.06	178.42	173.80	169.83	173.28	185.72	201.97
14.	Kolkata	152.61	178.73	213.37	237.88	231.01	192.62	165.76	172.21	167.97	167.18	159.21	143.19	181.75
15.	Machilipatnam	195.34	227.45	249.88	253.20	245.10	205.71	184.06	194.10	200.18	188.98	185.28	183.43	209.23
16.	Mangalore	199.30	214.75	208.90	246.49	208.91	157.40	133.60	165.42	189.59	183.40	167.71	160.82	186.08
17.	Minicoy	213.82	238.03	252.14	248.11	215.27	184.39	192.16	214.72	217.23	210.97	195.83	200.04	215.08
18.	Mohanbari	132.97	144.63	152.97	165.27	175.60	160.00	173.23	167.26	169.11	170.14	153.77	132.46	158.19
19.	Mumbai	187.28	222.65	253.90	275.01	274.82	196.08	151.82	163.91	187.51	205.00	186.57	172.67	206.25
20.	Nagpur	177.73	211.19	242.28	266.36	267.18	212.30	164.70	163.36	196.34	207.52	184.02	170.14	205.11
21.	New Delhi	143.42	180.26	228.02	267.04	267.32	250.59	209.68	200.51	205.38	189.98	156.98	132.41	202.63
22.	Okha	212.90	252.45	281.89	300.19	301.82	269.74	204.50	205.57	248.27	238.03	208.82	195.80	243.11
23.	Patiala	132.31	178.95	223.80	249.55	268.13	258.12	222.62	201.38	211.77	185.44	145.73	124.53	200.19
24.	Patna	146.16	194.93	234.31	256.71	257.08	225.58	185.62	194.35	191.62	187.97	164.21	135.27	197.71
25.	Port Blair	213.24	244.90	247.23	239.51	182.35	159.86	161.07	166.71	174.02	187.55	191.49	197.58	196.80
26.	Pune	197.59	232.78	262.81	283.49	289.75	219.36	177.63	179.08	206.17	212.91	201.56	186.90	220.66
27.	Rahuri	208.04	240.82	266.58	283.80	285.82	228.33	180.65	177.20	205.63	220.34	200.47	196.37	224.32
28.	Ranchi	180.06	209.02	238.42	252.61	247.48	194.90	163.46	164.19	170.38	187.28	176.27	170.68	196.10
29.	Shillong	163.12	186.32	214.46	228.41	204.54	179.62	174.49	167.70	155.30	162.47	173.07	158.10	180.55
30.	Srinagar	108.86	145.93	193.36	217.99	258.94	273.70	240.82	227.98	217.64	185.59	126.68	106.02	192.15
31.	Thiruvananthapuram	221.24	243.47	253.51	234.27	215.42	198.80	200.73	213.59	227.18	200.14	180.81	196.75	215.32
32.	Varanasi	144.14	190.14	237.18	261.08	256.95	222.19	187.14	196.39	191.32	191.39	162.43	136.72	198.03
33.	Visakhapatnam	192.26	222.46	240.25	257.26	245.35	196.16	179.33	185.71	192.91	199.27	185.42	180.18	206.23

November and December, respectively) whereas minimum GR is observed in Shillong (162.46 Wm^{-2} in October) and Amritsar (123.19 Wm^{-2} and 100.93 Wm^{-2} in November and December, respectively). The seasonal

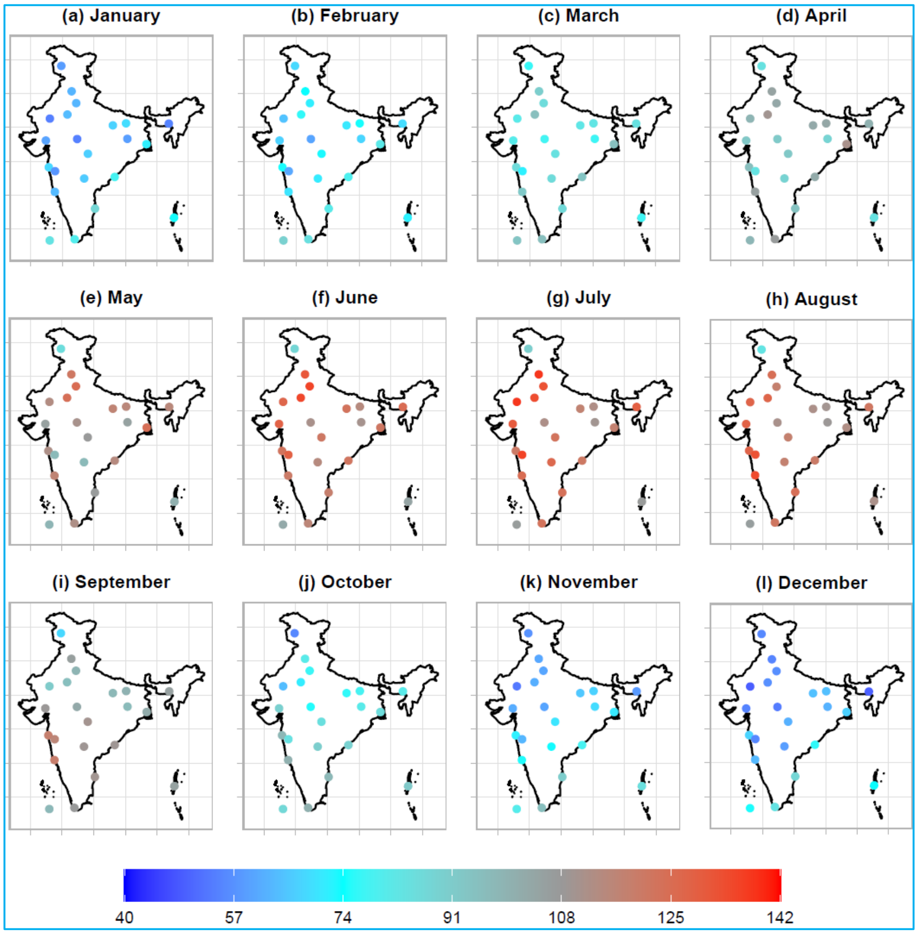


Fig. 3. Monthly mean of diffuse radiation (Wm^{-2}) during the period 1985-2019

variation of GR observed in the present study is inline with the values reported by Soni *et al*. (2012) and India Meteorological Department (2016, 2022, 2023).

3.2. *Monthly climatology of diffuse radiation*

Diffuse radiation (DR) is the radiation received per unit area on the earth's surface after scattering by atmospheric aerosols. The climatological monthly mean of DR for the period 1985-2019 is given in Fig. 3 and Table 2. Substantial monthly variation in DR is evident from the figure with a maximum during the monsoon and a minimum during the post monsoon or winter. Monthly variation of DR is discussed in this section.

Maximum DR during the winter season is observed in peninsular India and island stations. Chennai (87.55 Wm^{-2}) and Minicoy (89.39 Wm^{-2}) recorded the maximum in January and February, respectively. Meanwhile, minimum DR is observed in north and central India (Jodhpur (54.11 Wm^{-2}) and Bhopal (59.99 Wm^{-2}) in January and February, respectively). The DR over different stations in India is in the range 54.11-89.39 Wm^{-2} during the winter season.

The DR increases in the pre-monsoon over all the stations. Maximum DR during the pre-monsoon months is observed in Jaipur (95.37 Wm^{-2}), Kolkata (111.35 Wm^{-2}) and New Delhi (125.19 Wm^{-2}) in March, April and May, respectively. High DR over the Indo-Gangetic plains during the pre-monsoon is evident from Fig. 3. Meanwhile, minimum DR during the season is observed in Pune (71.85 Wm^{-2} and 81.36 Wm^{-2} in March and April, respectively) and Srinagar (85.23 Wm^{-2} in May). DR increases with an increase in cloudiness and turbidity of the atmosphere (Bhattacharya *et al*., 1996; Singh and Kumar, 2016). Therefore, the high DR over the Indo-Gangetic plains can be due to the increased pollution over the regions as reported by various studies, and low values over Pune and Srinagar can be due to the comparatively clean atmosphere over these regions. Further, it is observed that coastal stations also exhibit higher DR (compared to the inland stations), probably due to the presence of more clouds over coastal regions (Roy *et al*.,

TABLE 2

Monthly mean of diffuse radiation during the period 1985-2019

S. No.	Station	Diffuse Radiation (Wm^{-2})												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	Ahmedabad	59.81	67.05	80.30	92.31	105.48	128.37	130.49	128.17	108.42	89.52	61.21	54.73	92.30
2	Bhopal	54.32	59.99	77.72	91.53	111.15	111.35	112.20	111.30	102.50	75.02	59.92	53.75	85.20
3	Chennai	87.56	81.05	86.63	94.10	107.41	118.57	123.71	124.19	109.86	97.67	90.72	87.57	100.89
4	Goa	63.22	69.92	91.81	105.70	116.87	120.28	124.97	134.19	119.29	100.23	74.92	63.15	98.88
5	Hyderabad	65.96	70.98	85.84	88.51	97.01	114.46	126.22	118.04	109.12	90.32	73.54	58.78	91.68
6	Jaipur	63.60	76.03	95.37	109.84	124.18	134.64	133.61	127.21	95.28	71.28	61.51	56.64	95.88
7	Jodhpur	54.11	64.67	81.01	98.74	113.43	127.09	137.58	127.59	91.10	63.72	53.08	49.14	88.59
8	Kolkata	71.73	81.26	94.94	111.35	124.16	121.45	118.03	112.86	101.60	85.35	70.80	66.87	96.78
9	Minicoy	83.12	89.39	93.28	98.13	98.45	102.57	106.78	106.25	97.45	87.04	80.29	74.69	93.13
10	Mumbai	68.01	74.63	85.94	95.61	112.28	122.53	120.44	127.58	118.57	98.02	71.78	67.36	97.02
11	Nagpur	66.49	73.23	83.92	92.25	107.62	121.18	122.68	118.36	110.18	84.49	70.08	61.81	92.79
12	New Delhi	62.55	71.59	85.66	103.28	125.19	135.23	132.54	118.36	98.86	76.93	60.10	56.48	94.02
13	Patiala	62.46	73.78	90.11	104.77	121.27	131.00	137.60	124.39	106.12	80.93	60.45	54.92	95.78
14	Patna	68.66	74.48	82.65	103.31	115.57	114.46	112.66	109.96	99.49	78.23	66.93	64.11	90.95
15	Port Blair	74.51	71.93	77.44	83.60	100.43	104.16	107.47	111.66	105.03	91.75	84.69	73.79	90.65
16	Pune	57.47	60.51	71.86	83.37	96.84	128.67	135.66	132.34	115.89	83.82	62.76	55.48	90.55
17	Ranchi	58.98	67.63	77.14	88.25	105.08	110.61	109.82	108.53	96.62	80.95	68.62	62.09	86.29
18	Shillong	54.63	68.72	83.98	100.04	115.23	125.17	128.91	121.73	105.34	80.75	58.19	49.33	91.12
19	Srinagar	58.61	68.05	76.54	83.99	85.29	87.51	90.11	82.99	67.89	55.36	57.12	55.54	72.44
20	Thiruvananthapuram	79.82	84.46	95.35	107.34	112.51	115.93	123.15	121.86	107.72	100.25	95.22	83.16	102.33
21	Varanasi	67.05	70.54	82.11	102.47	116.92	122.88	117.37	111.95	97.57	75.99	65.39	64.40	91.33
22	Visakhapatnam	78.05	78.97	93.21	102.02	114.38	121.90	121.03	120.16	109.15	88.98	78.28	75.83	98.61

2015). The DR over various stations in India is in the range 71.85 - 125.19 Wm^{-2} during the pre-monsoon.

The DR further increases during the monsoon either due to the increased cloudiness or increased turbidity. Maximum DR during the season is observed in different stations during different months, whereas minimum DR is observed in Srinagar in all four months. Maximum DR is observed in New Delhi (135.22 Wm^{-2} in June), Patiala (137.60 Wm^{-2} in July) and Goa (134.18 Wm^{-2} and 119.29 Wm^{-2} in August and September respectively). The DR in Srinagar is 87.51 Wm^{-2}, 90.10 Wm^{-2}, 82.99 Wm^{-2} and 67.88 Wm^{-2} in June, July, August and September, respectively. An increase in DR is noticed from June to July over most of the stations. High DR during June-July is observed over northwest India, which shifts towards the west coast of peninsular India during August-September. Further, a decrease in DR from August to September is noticeable over all the stations. Overall, the DR over India is in the range 87.51-137.60 Wm^{-2} during the monsoon season.

Post monsoon exhibits less DR compared to pre-monsoon and monsoon seasons. More than 50% of the stations have minimum DR during the post monsoon season, especially in December. The remaining stations have minimum DR during the winter season. Maximum DR during the season is observed in Thiruvananthapuram (100.25 Wm^{-2} and 95.22 Wm^{-2} in October and November, respectively) and Chennai (87.57 Wm^{-2} in December). Whereas minimum DR during the season is observed in Srinagar (55.36 Wm^{-2} in October) and Jodhpur (53.07 Wm^{-2} and 49.13 Wm^{-2} in November and December, respectively). An increase in DR from north to south is evident, due to the prevalence of atmospheric stability and fewer clouds over the northern parts and clouds associated

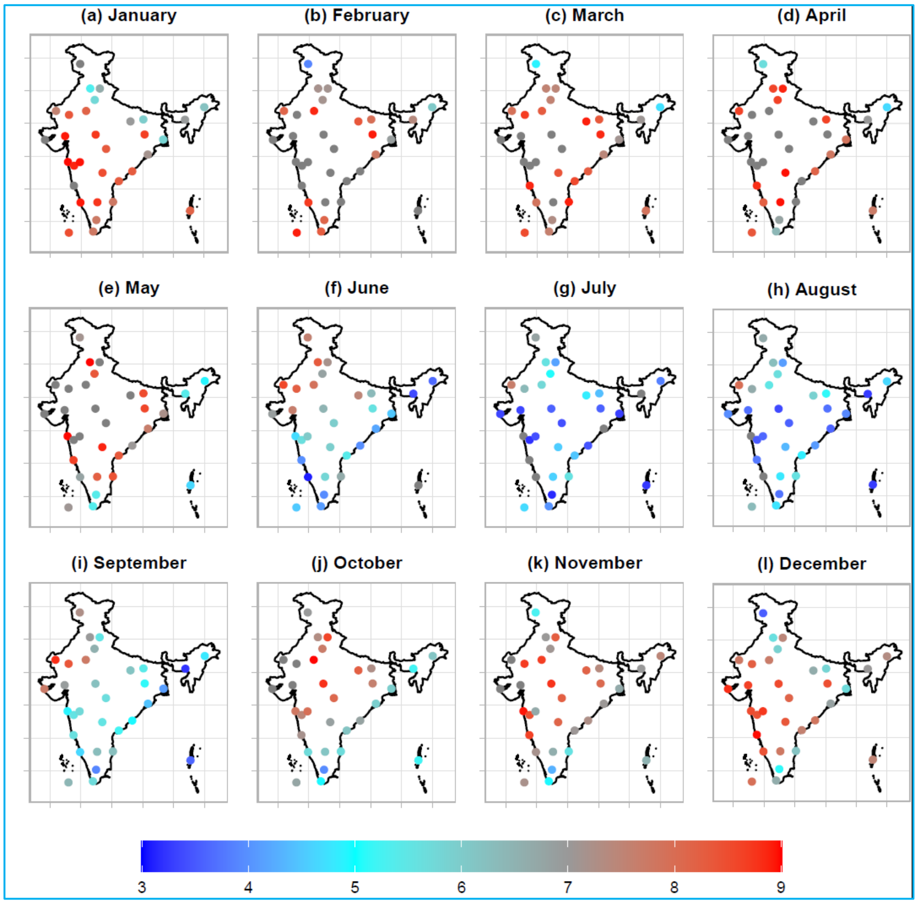


Fig. 4. Monthly mean of bright sunshine hours (hrs) during the period 1985-2019

with the post monsoon weather systems over the south peninsular India. In general, DR over Indian stations is in the range 53.07-100.25 Wm^{-2} during the post monsoon season). The values of DR observed in the study are in the order of DR values reported in Soni *et al*. (2012) and India Meteorological Department (2016, 2022, 2023).

3.3. *Monthly climatology of bright sunshine hours*

The monthly climatology of bright sunshine hours (BHS) over various stations in India during the study period is provided in Fig. 4 and Table 3. The BSH is mainly controlled by the cloudiness over the station and therefore it is maximum during the pre-monsoon (~80% of stations) season or winter (~20% of stations) and it is minimum during the monsoon (~90% of stations) or winter (~10% of stations).

In winter, maximum BHS is observed over central India and northwest of peninsular India. The high BHS over these regions is attributed to the less cloudiness as these regions rarely come under the direct influence of western disturbance and easterly waves; the weather producing systems over the north and south, respectively. Maximum BHS during the season is observed in Goa (9.4 hrs in January) and Rahuri (9.9 hrs. in February), respectively. Meanwhile, low BHS is observed over the northern parts of India due to the influence of western disturbance and associated cloudiness. The low BHS over the northern parts is also attributed to low day length during the winter season. Minimum value of BHS observed in Srinagar in both January (2.9 hrs) and February (3.9 hrs). Overall, BHS over the country varies from 2.9 hrs to 9.9 hrs during the winter.

BHS increases in pre-monsoon season. Maximum BHS in March is observed in Bengaluru (9.4 hrs) whereas that during April and May are observed in Ahmedabad (10.1 hrs, and 10.31 hrs, respectively). Minimum BHS during March and April are observed in Mohanbari (4.7 hrs and 4.7 hrs, respectively) and that in May is observed in Port Blair (4.6 hrs). Stations located in the extreme north, northeast and south of the country exhibit less values of BHS due to the cloudiness associated with various weather systems such as western disturbance, easterly troughs/cyclonic systems, *etc*.

TABLE 3

Monthly mean of bright sunshine hours for the period 1985-2019

S. No.	Station	Bright sunshine hours (hrs)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1.	Ahmedabad	8.9	9.7	9.4	10.1	10.3	7.6	3.3	3.7	6.9	9.1	9.1	8.6	8.1
2.	Bengaluru	8.8	9.7	9.4	9.0	8.2	5.8	4.6	4.8	6.3	6.1	6.6	7.8	7.2
3.	Bhopal	8.7	9.5	9.1	9.8	9.7	6.5	3.6	3.4	6.2	8.8	8.8	8.5	7.7
4.	Bhubaneshwar	7.1	7.8	7.4	7.8	7.7	4.2	2.8	3.6	4.5	5.9	7.0	6.8	6.0
5.	Chennai	7.8	9.1	8.9	9.3	8.4	6.7	5.6	5.6	6.2	5.7	5.6	6.2	7.1
6.	Dehradun	6.7	7.1	7.5	8.9	9.3	7.2	4.2	4.1	5.5	8.6	8.3	7.5	7.1
7.	Goa	9.5	9.9	8.9	8.8	8.6	4.0	2.7	3.8	5.6	7.2	8.6	9.0	7.2
8.	Hyderabad	8.5	9.3	8.4	9.0	8.9	6.0	4.5	4.4	5.5	6.9	8.1	8.4	7.3
9.	Jaipur	8.2	8.9	8.3	9.4	9.3	7.9	5.8	5.5	7.7	9.0	8.7	7.7	8.0
10.	Jaisalmer	7.6	8.1	7.9	8.6	9.5	8.6	7.7	8.0	8.8	9.4	9.1	7.8	8.4
11.	Jodhpur	8.4	9.0	8.7	9.8	9.9	8.2	6.4	6.6	8.4	9.3	8.7	8.2	8.5
12.	Kodaikanal	7.7	8.1	7.3	6.8	5.4	3.9	3.1	3.7	3.9	3.9	4.3	5.1	5.3
13.	Kolkata	5.8	6.9	7.1	7.9	7.2	4.5	3.3	3.9	4.1	5.9	6.7	5.7	5.7
14.	Machilipatnam	8.3	9.3	8.5	9.0	8.3	5.4	4.5	4.9	5.2	6.2	7.0	7.6	7.0
15.	Mangalore	8.9	8.7	7.9	8.2	6.8	3.1	1.9	2.9	4.6	5.7	7.2	8.4	6.2
16.	Minicoy	8.5	8.9	8.5	8.4	7.1	4.5	4.7	6.3	6.4	6.8	7.2	7.9	7.1
17.	Mohanbari	6.2	6.1	4.7	4.7	4.9	3.6	3.8	4.6	4.8	6.1	7.5	7.3	5.4
18.	Mumbai	9.0	9.7	9.3	9.6	9.0	4.7	2.3	2.6	4.9	7.8	8.9	8.5	7.2
19.	Nagpur	8.3	9.1	9.0	9.3	9.2	6.0	3.4	3.6	5.7	8.1	8.2	8.2	7.3
20.	New Delhi	5.8	7.1	7.6	8.6	8.4	6.8	5.1	5.6	6.6	7.7	7.1	5.9	6.8
21.	Okha	9.3	9.8	9.2	9.9	9.5	6.9	3.3	4.0	7.7	9.5	9.3	8.8	8.1
22.	Patiala	5.3	7.2	7.5	8.6	9.0	8.3	5.6	6.3	7.0	7.3	7.0	5.6	7.0
23.	Patna	6.0	8.0	8.3	8.6	8.5	6.3	4.4	5.1	5.4	7.3	7.4	5.8	6.8
24.	PortBlair	8.2	9.1	7.9	7.7	4.6	3.0	3.2	3.3	3.6	5.2	6.5	7.5	5.8
25.	Pune	8.9	9.7	9.4	9.7	9.8	5.6	3.2	3.5	5.5	7.5	8.5	8.4	7.5
26.	Rahuri	9.0	9.9	9.1	9.7	9.8	6.0	3.4	3.6	5.7	8.0	6.7	8.7	7.5
27.	Ranchi	8.7	8.9	8.8	9.1	8.6	5.6	3.6	3.7	5.1	7.6	8.1	8.5	7.2
28.	Shillong	7.0	7.4	7.1	7.0	5.4	3.4	3.0	3.3	3.2	5.2	7.0	7.0	5.5
29.	Srinagar	2.9	3.9	4.9	5.7	7.1	7.6	6.8	6.7	7.3	7.0	5.3	3.5	5.7
30.	Thiruvananthapuram	7.8	8.3	7.6	6.4	5.3	4.1	4.0	4.8	5.7	4.9	4.9	6.6	5.9
31.	Varanasi	7.0	8.4	8.9	9.5	9.6	7.5	4.8	5.9	6.1	8.2	8.2	6.6	7.6
32.	Visakhapatnam	8.3	9.2	8.3	8.2	7.0	4.0	3.5	4.1	4.9	6.8	7.3	7.8	6.6

Further, it can be noted that BHS increases from May to June over the stations in north India, whereas that over the south and northeast parts decreases due to the pre-monsoon showers. Overall, BHS varies from 4.6 hrs to 10.3 hrs over various stations during the season.

BHS drastically reduces during the monsoon due to organized cloudiness associated with the monsoon system. However, the stations in the extreme northwest do not exhibit the reduction. The BHS ranges from 1.9 hrs to 8.8 hrs over various stations during the season. A shift of

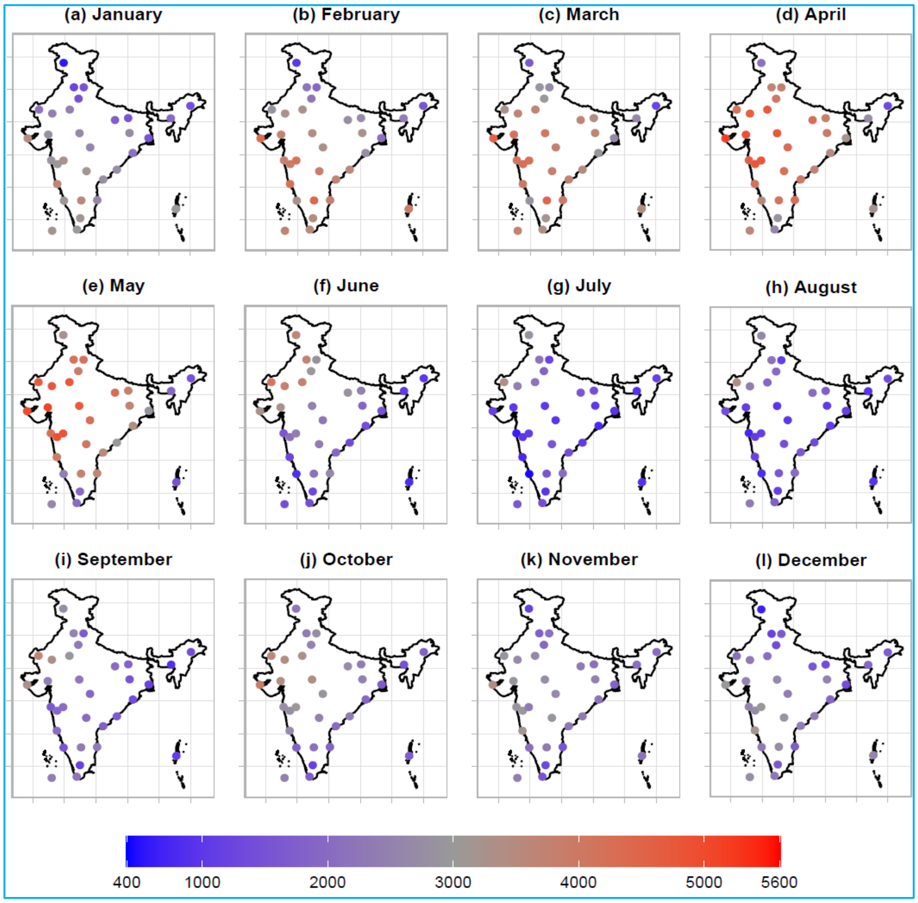


Fig. 5. Monthly mean of SPV potential (Wm^{-2}) for the period 1985-2019

the BHS minimum from south to northern parts of India is evident from June to July, which is in line with the progression of monsoon over the country (Pai *et al.*, 2020). Maximum BHS during the season is observed in Jaisalmer (8.6 hrs, 7.7 hrs, 8.0 hrs, 8.8 hrs in June, July, August and September, respectively), whereas minimum BHS is observed in Port Blair (3.0 hrs), Mangalore (1.9 hrs), Mumbai (2.6 hrs) and Shillong (3.2 hrs) in June, July, August and September, respectively. BHS is high over north and northwest India, and eastern parts of peninsular India whereas it is low over the west coast and northeast regions, which is in line with the rainfall pattern during the season (Pai *et al.*, 2015).

As the monsoon withdraws from the entire country in October (Pai *et al.*, 2020), the decrease in rainfall and associated cloudiness causes BHS to increase from the monsoon to the post monsoon. Therefore, BHS during the post monsoon season is in the range 3.5-9.3 hrs over the country. The maximum BHS in October and November are observed in Okha (9.5 hrs and 9.3 hrs, respectively) and that in December is observed in Goa (9.0 hrs). However, minimum BHS during the season is observed in Kodaikanal (3.9 hrs and 4.3 hrs in October and November, respectively) and Srinagar (3.5 hrs in December). Northern and southern parts of the country exhibit low BHS due to the influence of western disturbances and easterly waves/cyclonic disturbances over the regions. The region of high BHS is located over northwest India during October and November and shifts to the northwest of peninsular India in December. The values of BHS observed in the study are in line with the values reported in Soni *et al.* (2012) and India Meteorological Department (2016, 2022, 2023).

3.4. *Monthly climatology of technical potential of solar electricity generation*

In the wake of the increased energy demand and the need for non-renewable alternates for large scale power generation, tropical country like India has a huge scope in the production of solar electricity. Monthly climatology of the technical potential of solar power (SPV potential) aids to identify the spatial and monthly variation of technical potential of solar power generation over different parts of India (Fig. 5 and Table 4). The SPV potential is a measure

TABLE 4

Monthly mean of SPV potential for the period 1985-2019

S. No.	Station	SPV potential (Wm^{-2})												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1.	Ahmedabad	2821.5	3659.6	4165.2	4933.9	5092.3	3216.8	989.1	1077.1	2467.6	3347.3	2932.5	2545.5	2997.6
2.	Bengaluru	3582.5	4451.6	4482.3	4152.2	3689.7	2166.2	1525.6	1600.4	2354.5	2126.2	2275.0	2739.3	2839.5
3.	Bhopal	2608.4	3399.5	4026.5	4788.3	4686.0	2470.4	1041.4	953.4	2249.4	3304.3	2782.0	2644.7	2815.8
4.	Bhubaneshwar	2164.6	2745.3	2911.1	3402.4	3341.8	1395.5	778.4	1085.7	1379.4	1919.1	2194.5	1964.9	2045.9
5.	Chennai	2610.8	3699.9	3952.3	4217.9	3619.6	2618.6	2044.2	2050.9	2348.0	1802.2	1545.8	1726.0	2616.9
6.	Dehradun	1476.3	1931.7	2684.0	3785.6	4173.0	2810.8	1222.1	1116.6	1697.5	2740.3	2123.3	1608.0	2224.6
7.	Goa	3574.8	4207.6	3983.8	4124.2	3940.3	1253.8	748.8	1190.5	2048.4	2664.0	3149.9	3178.0	2718.3
8.	Hyderabad	3113.7	3873.8	3810.6	4232.5	4082.8	2346.0	1545.9	1440.2	2021.4	2492.7	2927.7	2870.5	2836.1
9.	Jaipur	2430.1	3211.0	3651.8	4714.4	4753.9	3701.3	2171.4	1891.6	2964.9	3256.8	2645.1	2079.2	3085.0
10.	Jaisalmer	2205.9	2839.0	3243.3	4081.9	4697.5	4066.2	3328.0	3406.4	3656.8	3558.9	2871.1	2108.4	3321.7
11.	Jodhpur	2435.1	3201.9	3652.6	4636.0	4814.5	3784.7	2423.6	2373.4	3334.8	3432.9	2626.1	2291.9	3222.5
12.	Kodaikanal	3120.9	3479.7	3159.3	2861.6	1984.8	1264.9	946.8	1151.2	1170.8	1158.0	1287.4	1643.1	1840.8
13.	Kolkata	1543.8	2134.5	2627.9	3237.6	2886.4	1497.2	942.3	1163.3	1194.0	1720.6	1834.4	1410.4	1806.4
14.	Machilipatnam	2801.9	3659.3	3695.1	3947.3	3534.7	1919.1	1425.5	1628.6	1807.2	2011.3	2258.8	2407.4	2534.6
15.	Mangalore	3081.5	3235.0	2841.8	3513.9	2457.6	840.4	437.6	823.1	1521.6	1807.9	2081.4	2341.6	1988.9
16.	Minicoy	3139.6	3669.2	3719.7	3589.6	2631.4	1440.7	1551.7	2354.3	2415.1	2470.6	2437.0	2749.4	2638.5
17.	Mohanbari	1423.6	1513.8	1249.6	1333.9	1493.2	1006.1	1152.2	1344.5	1403.6	1805.9	1985.7	1680.2	1467.7
18.	Mumbai	2909.6	3733.8	4092.0	4572.5	4270.8	1587.8	615.9	728.6	1589.0	2766.9	2888.3	2544.6	2560.7
19.	Nagpur	2555.2	3320.4	3787.8	4308.0	4252.0	2196.7	974.2	1007.2	1920.1	2903.5	2621.1	2399.8	2599.3
20.	New Delhi	1429.2	2226.4	2980.6	3989.2	3866.9	2957.0	1835.2	1958.2	2327.3	2527.0	1924.4	1349.2	2398.5
21.	Okha	3408.6	4261.4	4477.9	5146.5	4964.8	3222.2	1178.6	1406.3	3309.6	3897.8	3349.9	2989.4	3394.8
22.	Patiala	1214.4	2220.3	2917.7	3711.6	4171.3	3708.2	2144.7	2187.3	2566.5	2345.8	1767.1	1209.5	2441.5
23.	Patna	1513.1	2682.8	3382.2	3831.9	3790.1	2474.0	1416.7	1719.8	1794.1	2365.8	2097.1	1363.0	2310.3
24.	PortBlair	3016.9	3871.3	3369.9	3191.9	1463.9	816.2	902.4	942.7	1083.7	1689.2	2149.6	2570.4	1973.7
25.	Pune	3034.3	3925.7	4251.5	4780.2	4914.8	2134.4	981.0	1087.8	1975.0	2751.2	2952.8	2729.9	2849.3
26.	Rahuri	3224.5	4132.5	4197.9	4778.1	4850.3	2383.6	1066.8	1108.2	2043.9	3035.5	2315.2	2966.9	2894.9
27.	Ranchi	2697.7	3225.9	3649.6	3978.0	3672.9	1875.6	1008.7	1052.4	1507.2	2465.3	2457.9	2503.4	2433.1
28.	Shillong	1962.4	2378.8	2619.5	2762.5	1906.3	1050.0	900.3	943.3	862.7	1466.1	2095.7	1919.0	1709.8
29.	Srinagar	554.5	982.5	1635.6	2136.8	3192.4	3587.3	2832.3	2625.1	2734.0	2243.9	1155.1	647.6	1902.7
30.	Thiruvananthapuram	2978.7	3488.2	3339.4	2595.9	1993.0	1408.2	1394.6	1758.4	2237.5	1713.5	1548.0	2249.6	2183.5
31.	Varanasi	1741.9	2750.8	3653.1	4302.2	4287.3	2878.0	1567.6	2002.1	2035.1	2725.4	2296.4	1566.8	2589.6
32.	Visakhapatnam	2759.5	3529.6	3443.7	3627.6	2985.3	1347.2	1070.4	1311.4	1651.0	2347.4	2327.6	2439.9	2351.6

of the potential of a station to produce electricity from solar energy in the standard test conditions, as provided in Section 2. Stations with high SPV can produce more electricity per unit time compared to stations with low SPV.

In winter, SPV potential over the country is in the range 554.54-4451.57 Wm^{-2} with substantial regional variation. High SPV potential is over peninsular India which decreases towards the north; however, SPV potential over the south and southwest stations in

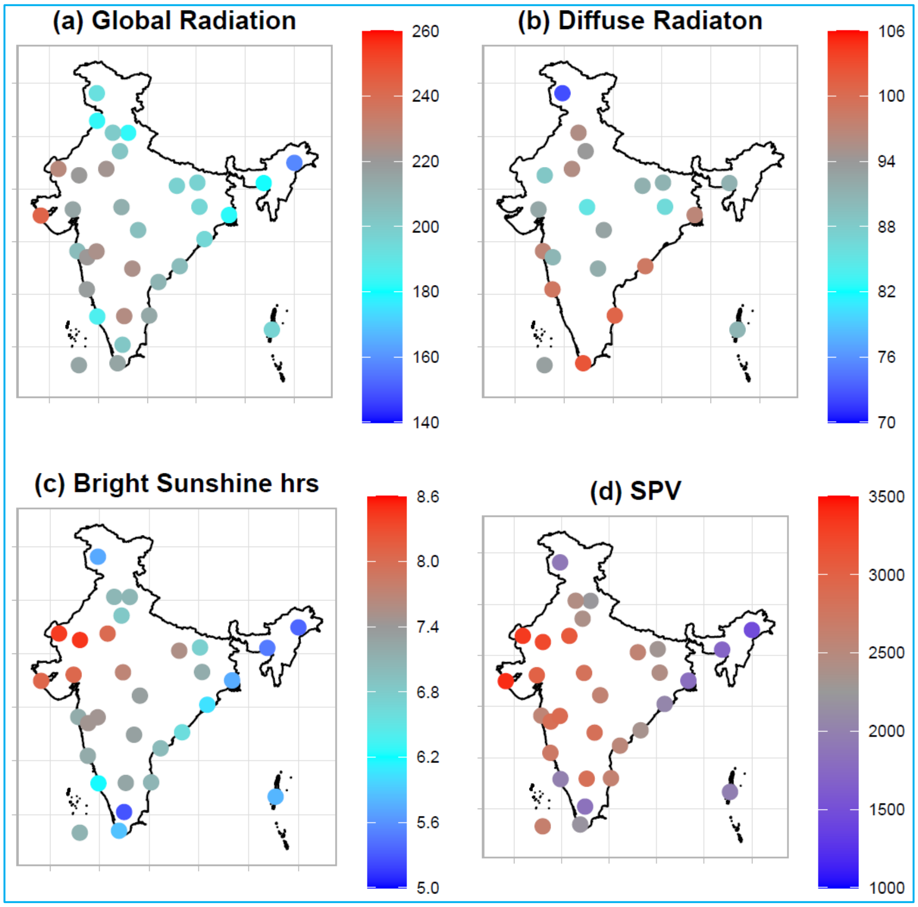


Fig. 6. Annual mean of (a) global radiation (Wm^{-2}) (b) diffuse radiation (Wm^{-2}) (c) bright sunshine hours (hrs) and (d) SPV potential (Wm^{-2}) during the period 1985-2019

peninsular India exhibits low SPV potential due to reduced bright sunshine hours, which is attributed to the comparatively high amount of cloudiness over the stations. There is a noticeable increase in SPV potential from January to February in all stations due to the apparent movement of the sun towards the northern hemisphere and the subsequent increase in solar radiation. Maximum SPV potential during the season is in Bengaluru (3582.5 Wm^{-2} and 4451.57 Wm^{-2} in January and February, respectively) whereas minimum SPV potential is in Srinagar (554.54 Wm^{-2} and 982.54 Wm^{-2} in January and February, respectively).

SPV potential has a substantial increase from winter to pre-monsoon, and it is in the range 1249.63-5146.5 Wm^{-2} during the pre-monsoon season. Maximum SPV potential during the pre-monsoon is observed in Bengaluru (4482.3 Wm^{-2}), Okha (5146.5 Wm^{-2}) and Ahmedabad (5092.3 Wm^{-2}) in March, April and May, respectively, whereas minimum SPV potential is in Mohanbari during March-April (1249.6 Wm^{-2} and 1333.9 Wm^{-2}, respectively) and Port Blair during May (1463.8 Wm^{-2}). A considerable increase in SPV potential is observed from March to April in most of the stations over central, north and northwest India; however, it decreased in May except over the extreme northwest regions where it continued to increase. This is in line with the variations in GR and BHS over the regions.

The enhanced cloudiness and rainfall drastically reduce the SPV potential over the country during the monsoon season. Maximum SPV potential during the season is observed in Jaisalmer (4066.2 Wm^{-2}, 3328.0 Wm^{-2}, 3406.4 Wm^{-2} and 3656.8 Wm^{-2} in June, July, August and September, respectively) which is located in the northwest of the country where the seasonal shallow ‘heat low’ prevails. While, minimum SPV potential is observed in Port Blair (816.2 Wm^{-2}), Mangalore (437.6 Wm^{-2}), Mumbai (728.6 Wm^{-2}) and Shillong (862.7 Wm^{-2}) in June, July, August and September, respectively. Low SPV potential is evident over the west coast and northeast regions where the seasonal rainfall is high. Further, it is noted that the SPV potential over the country is minimum during July-August (also called the peak monsoon

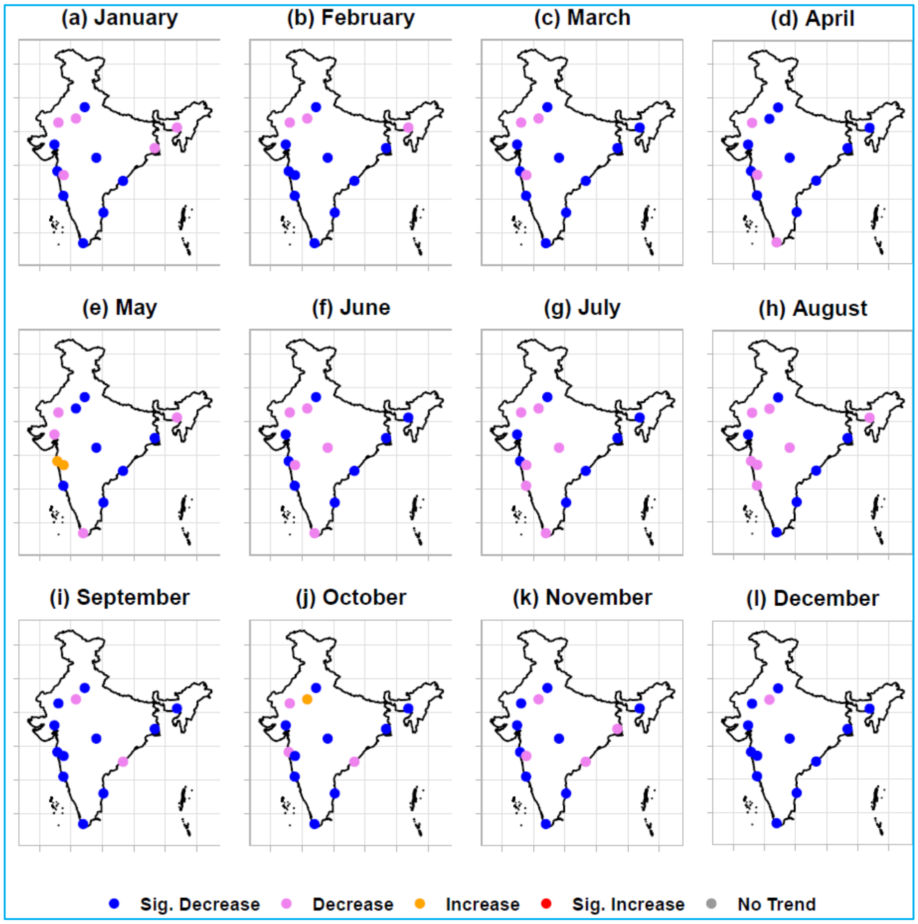


Fig. 7. Month wise trend of global radiation during the period 1985-2019

months) when the monsoon rainfall as well as the monsoon circulations attain their peaks (Sudeep kumar *et al*., 2018).

SPV potential slightly increases over most of the stations during the post monsoon season; however, it decreases over north India due to the reduction in the solar radiation and BHS due to the apparent movement of the sun towards the southern hemisphere. In southern peninsular India, the SPV potential slightly increases from monsoon to post monsoon. Though, the SPV potential is comparatively low over the region, which is attributed to the cloudiness and rainfall due to the northeast monsoon. Therefore, maximum SPV potential during October-November is observed in Okha (3897.8 Wm^{-2} and 3350.0Wm^{-2}) and that during December is observed in Goa (3178.0 Wm^{-2}). Minimum SPV potential in October is observed in Kodaikanal (1158.0 Wm^{-2}) and that during November-December is observed in Srinagar (1155.1 Wm^{-2} and 647.6 Wm^{-2} in November and December, respectively).

3.5. *Annual climatology of solar radiation, bright sunshine hours and SPV potential*

Annual climatology of GR, DR, BHS and SPV potential are provided in Fig. 6. Annual GR is maximum in Okha (243.11 Wm^{-2}) and minimum in Mohanbari (158.19 Wm^{-2}). High (low) GR is observed mainly in northwest and inland areas of peninsular India (extreme north and northeast). DR has different spatial patterns over the country. The DR is maximum in Thiruvananthapuram (102.33 Wm^{-2}) whereas the minimum DR is observed in Srinagar (72.43 Wm^{-2}). High annual DR is observed in the coastal stations such as Thiruvananthapuram, Chennai, Goa, Vishakhapatnam and Mumbai (97.02-102.33 Wm^{-2}), attributed to the high humidity and cloudiness over the stations. BHS is high in the northwest, whereas it is low over extreme north, northeast as well as south peninsular India. Maximum BHS is observed in Jodhpur (8.5 hrs) whereas minimum BHS is observed in Kodaikanal (5.3 hrs). The spatial pattern of SPV potential is analogous to that of BHS; high values are over the northwest and low

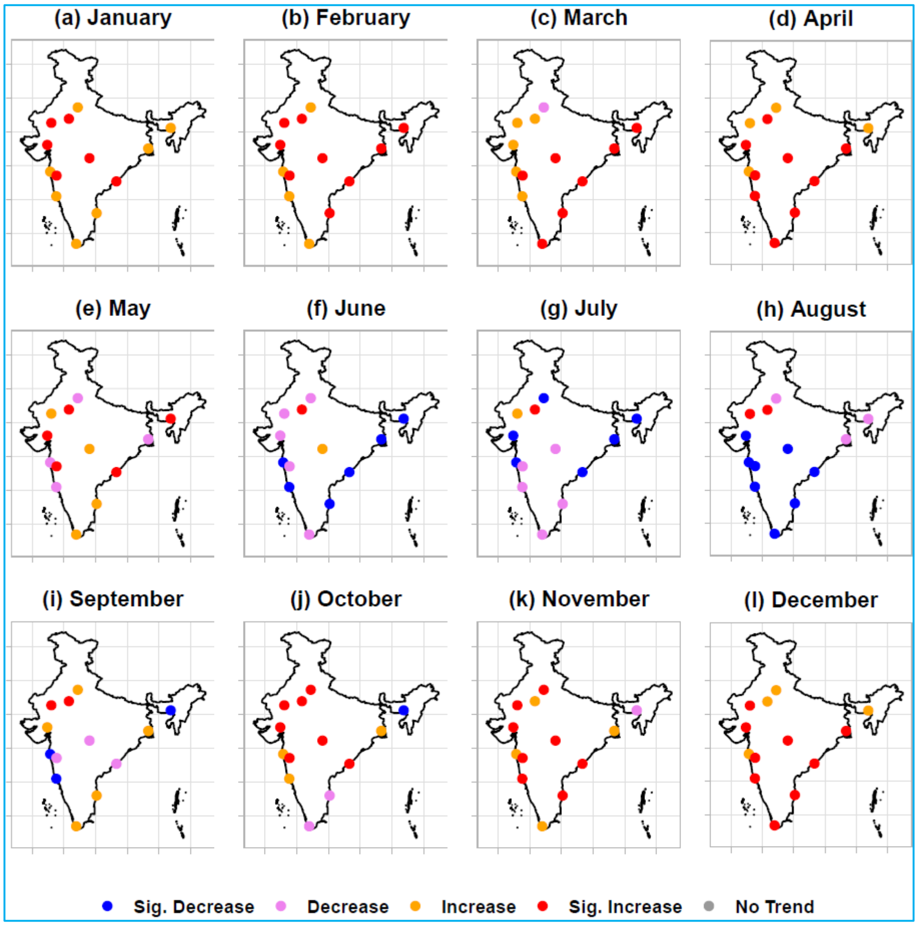


Fig. 8. Month wise trend of diffuse radiation during the period 1985-2019

values are over the extreme north, northeast as well as the south peninsular India. Maximum SPV potential is observed in Okha (3394.8 Wm^{-2}) whereas minimum SPV potential is observed in Mohanbari (1467.71 Wm^{-2}). The annual values of SPV potential obtained in the present study are in line with the estimation of the same from satellite observations as reported by Mahtta *et al*. (2014). However, it must be noted that district wise SPV potentials was depicted in their study, whereas the present study discusses the station wise SPV potentials.

3.6. *Monthly trend of global radiation*

Monthly trends of global radiation over the stations in India is depicted in Fig. 7. Stations which do not have continuous data gap of 5 years (or more) during the study period have been selected for the trend analysis, and therefore the number of stations is reduced to 13. Significant trends were identified using *student's t test*. A homogenous decreasing trend is observed in all the stations during all the months except May and October, where a few stations exhibit the opposite trends.

In January, New Delhi, Ahmedabad, Nagpur, Mumbai, Visakhapatnam, Goa, Chennai and Thiruvananthapuram have significant (at 0.05 level) decreasing trends in global radiation. The remaining station such as Jodhpur, Jaipur, Shillong, Kolkata and Pune have decreasing trends, but they are statistically not significant. All stations except Jodhpur, Jaipur and Shillong have a significant decreasing trend in February; whereas these stations have a decreasing trend that is statistically not significant.

A significant decreasing trend (at 0.05 level) in global radiation is evident in all stations during March, except Jaipur, Jodhpur and Pune; where the decreasing trend is statistically not significant. In April, the stations with the insignificant decreasing trends are Jodhpur, Pune and Thiruvananthapuram; all other stations have significant decreasing trends at 0.05 level. However, in May New Delhi, Jaipur, Kolkata, Nagpur, Visakhapatnam, Goa and Chennai have significant decreasing whereas Jodhpur, Shillong, Ahmedabad and Thiruvananthapuram have decreasing trend but statistically not significant. The stations Mumbai and Pune have statistically insignificant increasing trends during the period.

The number of stations with significant decreasing trend has decreased from ~70% during winter and pre-monsoon season to less than 50% during the monsoon season. In June, New Delhi, Shillong, Ahmedabad, Kolkata, Mumbai, Visakhapatnam, Goa and Chennai have significant decreasing trends (at 0.05 level) and Jodhpur, Jaipur, Nagpur, Pune and Thiruvananthapuram have an increasing trend that is statistically insignificant. All the stations with a significant decreasing trend in June (except Goa) have a significant decreasing trend (at 0.05 level) in July as well. However, the decreasing trend in Goa is not statistically significant in July. In August, New Delhi, Ahmedabad, Kolkata, Visakhapatnam, Chennai and Thiruvananthapuram have a significant decreasing trend (at 0.05 level) whereas the remaining stations have a statistically insignificant decreasing trend. While all the stations except Jaipur and Vishakhapatnam have a significant decreasing trend (at 0.05 level) in September. Jaipur and Vishakhapatnam have decreasing trend during the month, but the trend is statistically insignificant.

About 70% (90%) of the stations have a significant decreasing trend (at 0.05 level) in October and November (December). In October, New Delhi, Shillong, Ahmedabad, Kolkata, Nagpur, Pune, Goa, Chennai and Thiruvananthapuram have significant decreasing trend (at 0.05 level). The remaining stations except Jaipur have a statistically insignificant decreasing trend; a statistically insignificant increasing trend is observed in Jaipur. In the case of November month, New Delhi, Jodhpur, Shillong, Ahmedabad, Nagpur, Mumbai, Goa, Chennai and Thiruvananthapuram have significant decreasing trend (at 0.05 level), and the remaining stations have decreasing trend that is statistically insignificant. All the stations except Jaipur have significant decreasing trend (at 0.05 level) during December. In Jaipur, the decreasing trend is statistically insignificant.

We also studied the decadal variation of GR during three decades 1985-1994 (Decade 1), 1995-2004 (Decade 2) and 2005-2014 (Decade 3) (Figure not shown), which shows consistent decrease in global radiation from Decade 1 to Decade 2 as well as from Decade 2 to Decade 3. However, the declining trend has been considerably reduced (increased) from Decade 2 to Decade 3 during winter, pre-monsoon and post monsoon (monsoon) seasons. It is in line with the observations by Soni *et al*., (2016).

3.7. *Monthly trend of diffuse radiation*

Monthly trends of diffuse radiation over various stations in India are depicted in Fig. 8. The trends of diffuse radiation are entirely different from that of global radiation and it has substantial seasonal variation as well. A homogenous increasing trend (with varying significance level) in diffuse radiation is observed during winter months (Jan-Feb), April and December. However, the trends during other months are inhomogeneous and varies from station to station. The trends obtained in the present study are in line with the trends reported in the literature.

In the month of January, a significant increasing trend (at 0.05 level) is observed in Jodhpur, Jaipur, Ahmedabad, Nagpur, Pune and Visakhapatnam, whereas New Delhi, Shillong, Kolkata, Mumbai, Visakhapatnam, Goa, Chennai and Thiruvananthapuram have an increasing trend that is statistically not significant. In February, Jodhpur, Jaipur, Shillong, Ahmedabad, Kolkata, Nagpur, Pune, Vishakhapatnam and Chennai have significant increasing trends (at 0.05 level), and the remaining stations have an increasing trend that is statistically insignificant.

Shillong, Kolkata, Nagpur, Pune, Visakhapatnam, Chennai and Thiruvananthapuram have significant increasing trends (at 0.05 level) in March. The remaining stations except New Delhi have increasing trend that is statistically insignificant; in New Delhi, an increasing trend is observed which is also statistically insignificant. In April all the stations except New Delhi, Jodhpur, Shillong and Mumbai have significant increasing trend (at 0.05 level); these stations have increasing trend which is statistically insignificant. In May contrasting trends are observed across various stations. Jaipur, Shillong, Ahmedabad, Pune and Visakhapatnam have significant increasing trend (at 0.05 level), Jodhpur, Nagpur, Chennai and Thiruvananthapuram have statistically insignificant increasing trend, and New Delhi, Kolkata, Mumbai and Goa have decreasing trend that is statistically insignificant.

Trends of DR during the monsoon months are different from that of other seasons. Most of the stations exhibit a decreasing trend in diffuse radiation during the season, in line with the trend in global radiation. In the month of June, Shillong, Kolkata, Mumbai, Visakhapatnam, Goa and Chennai have significant decreasing trend (at 0.05 level) and New Delhi, Jodhpur, Ahmedabad, Pune and Thiruvananthapuram have decreasing trends that are statistically not significant. However, Jaipur and Nagpur have increasing trend in which the former is statistically significant (at 0.05 level) and the latter is statistically insignificant. In July, New Delhi, Shillong, Ahmedabad, Kolkata, Mumbai and Visakhapatnam have significant decreasing trend (at 0.05 level) whereas Nagpur, Goa, Chennai and Thiruvananthapuram have decreasing trend that are

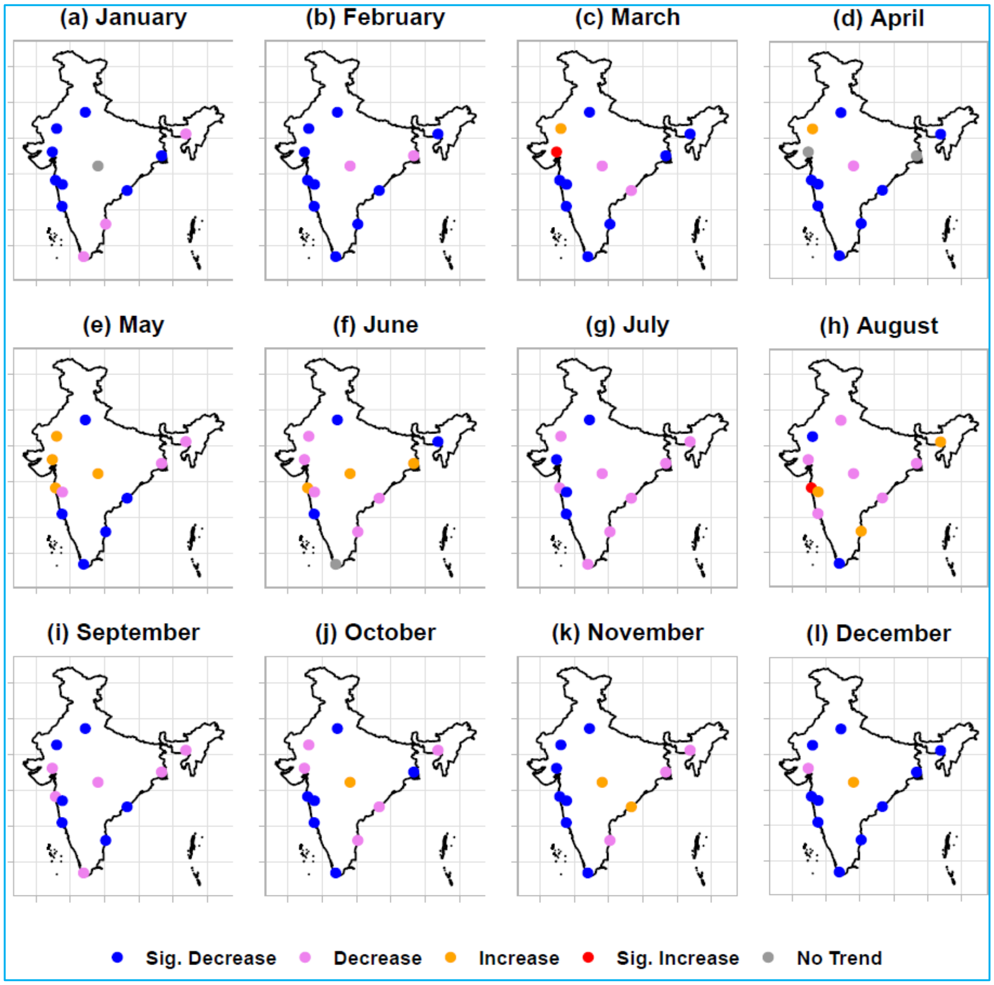


Fig. 9. Month wise trend of bright sunshine hours during 1985-2019

statistically insignificant. Jaipur and Jodhpur have increasing trend in diffuse radiation in which the trend is statistically significant (at 0.05 level) for the former and insignificant for the latter. In the case of August, Ahmedabad, Nagpur, Mumbai, Pune, Visakhapatnam, Goa, Chennai and Thiruvananthapuram have significant decreasing trends (at 0.05 level) whereas New Delhi, Shillong and Kolkata have decreasing trend but statistically not significant. Contrarily, a significant increase in diffuse radiation (at 0.05 level) is observed in Jodhpur and Jaipur. The trend pattern changes from September onwards. Nearly 50% of the stations exhibit decreasing trend during the season, out of which three stations have a significant decrease (Mumbai, Goa and Shillong) and the remaining three (Pune, Nagpur and Vishakhapatnam) have a decrease that is statistically not significant.

The trend pattern gets reversed in the post monsoon and most of the stations exhibit increasing trends in diffuse radiation during the season. In October all stations except those in the southern parts of peninsular India and northeast India exhibit an increasing trend, whereas the stations in southern peninsular India (Thiruvananthapuram and Chennai) and northeast India (Shillong) exhibit a decreasing trend. Although, the increasing trends in Mumbai, Goa and Kolkata are statistically insignificant. In November, all the stations except Shillong have a significant increasing trend. Out of those stations Jaipur, Mumbai, Thiruvananthapuram and Kolkata have statistically insignificant increasing trends, whereas the remaining stations have statistically significant (at 0.05level) increasing trends. In December, all the stations exhibit an increasing trend, out of which the trends over New Delhi, Jaipur, Mumbai and Shillong are statistically insignificant.

Decadal variation of DR during three decades 1985-1994 (Decade 1), 1995-2004 (Decade 2) and 2005-2014 (Decade 3) (Figure not shown) indicates that increasing

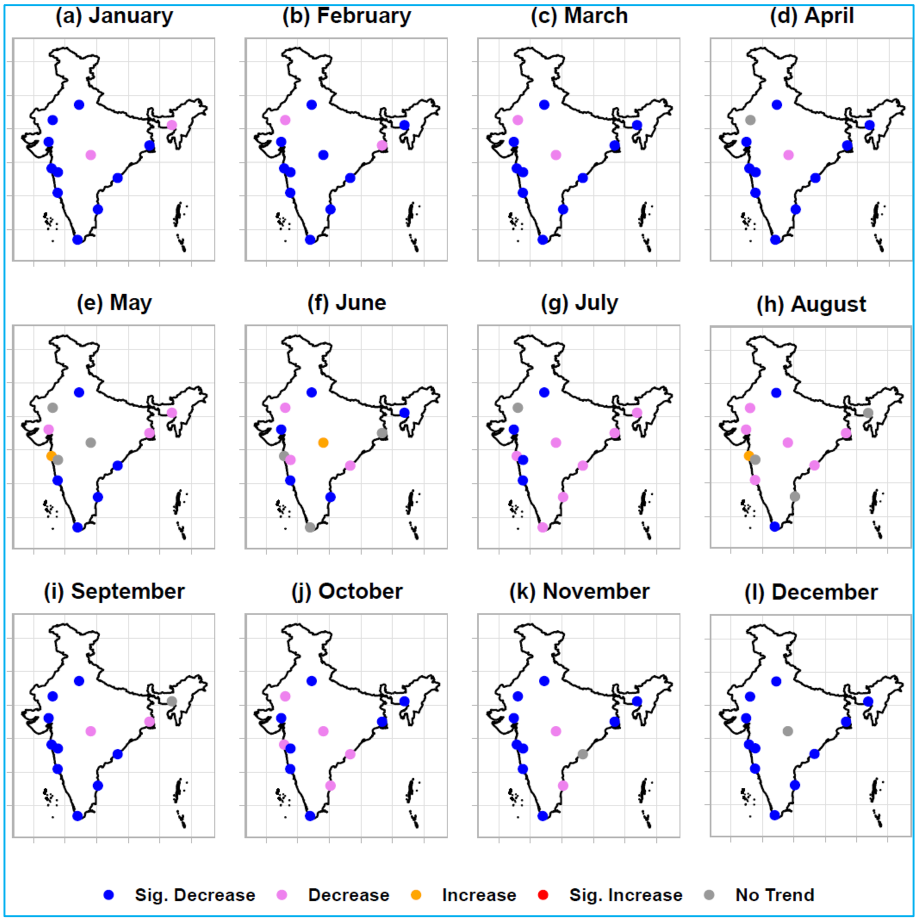


Fig. 10. Month wise trend of SPV potential during the period 1985-2019

trend has been escalated from Decade 2 to Decade 3 in winter, pre-monsoon and post monsoon. Similarly, the decreasing trend during the monsoon season also has been escalated from Decade 2 to Decade 3.Soni *et al*. (2016) observed a less pronounced trends and complex spatial pattern in DR during 1971-2010. However, observations from the present study provides a better understanding of the trend in DR over the country.

3.8. *Monthly trend of bright sunshine hours*

Fig. 9 illustrates the trend of BHS over different stations in India. A homogenous increasing trend is observed in all the stations during winter months (Jan-Feb), July and September whereas the trend is inhomogeneous during other months.

All stations except Nagpur have a decreasing trend in January, out of which the trends in Shillong, Chennai and Thiruvananthapuram are statistically insignificant and the trends over the other stations are significant at 0.05 level. Nagpur does not exhibit any trend during the month. In February, all stations exhibit a significant (at 0.05 level) decreasing trend except in Nagpur and Kolkata where decreasing trends are observed which are statistically not significant.

In March all stations except two in northwest India (Jodhpur and Ahmedabad) exhibit decreasing trend in BHS, out of which the trends in Nagpur and Vishakhapatnam are statistically insignificant. In Jodhpur, an increasing trend is observed which is statistically insignificant whereas in Ahmedabad, a significant (at 0.05 level) increasing trend is observed. In April, all stations except three (Jodhpur, Ahmedabad and Kolkata) exhibit a decreasing trend. All these trends are statistically significant (at 0.05 level) except in Nagpur where it is insignificant. There is no visible trend in Ahmedabad and Kolkata, whereas an increasing trend is evident in Jodhpur which is statistically not significant. In May, New Delhi, Visakhapatnam, Goa, Chennai and Thiruvananthapuram have a significant decreasing trend (at 0.05 level), whereas Shillong, Kolkata and Pune have decreasing trend which are statistically not significant. The remaining stations

TABLE 5

Trend of SPV potential (Wm^{-2}) during the period 1985-2019

S. No.	Station	Trend of SPV Potential (Wm^{-2})												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1.	Ahmedabad	-20.2	-25.52	-15.08	-24.56	-6.15	-21.98	-15.48	-8.32	-27.02	-21.4	-30.29	-13.98	-22.62
2.	Chennai	-18.2	-25.19	-24.1	-32.3	-29.87	-18.3	-10.22	0	-19.53	-13.48	-11.49	-30.44	-21.0
3.	Goa	-33.47	-34.97	-42.13	-50.18	-36.94	-17.62	-14.92	-8.84	-38.77	-30.52	-30.17	-35.24	-32.43
4.	Jodhpur	-12.65	-8.5	-11.16	0	0	-14.36	0	-18.61	-23.66	-9.11	-30.38	-14.52	-9.09
5.	Kolkata	-24.04	-17.54	-24.35	-19.52	-22.57	0	-5.84	-14.91	-9.13	-29.5	-13.53	-22.41	-7.42
6.	Mumbai	-29.23	-16.49	-18.95	-20.23	16.47	0	-17.25	13.7	-28.34	-22.21	-18.07	-26.33	-14.1
7.	Nagpur	-8.7	-21.92	-11.99	-18.95	0	7.15	-6.2	-9.47	-17.6	-7.75	-6.21	0	-7.04
8.	New Delhi	-37.21	-29.09	-27.39	-43.09	-63.82	-59.04	-32.44	-23.2	-50.94	-32.52	-54.08	-25.88	-45.65
9.	Pune	-16.52	-22.74	-17.98	-14.57	0	-8.67	-19.46	0	-25.13	-25.09	-13.53	-19.86	-15.78
10.	Shillong	-5.31	-19.96	-29.8	-30.07	-6.96	-15.93	-7.79	0	0	-17.13	-16.46	-22.83	-13.03
11.	Thiruvananthapuram	-19.01	-29.03	-45.19	-21.14	-23.89	0	-15.6	-21.71	-21.55	-28.19	-32.35	-43.51	-22.16
12.	Visakhapatnam	-27.25	-38.48	-29.07	-35.16	-46.12	-11.23	-12.49	-14.42	-15.57	-7.04	0	-38.57	-20.52

such as Jodhpur, Ahmedabad, Nagpur and Mumbai have increasing trends that are statistically not significant. Stations in peninsular India and north India exhibit significant decreasing trends during pre-monsoon months, whereas stations in the northwest show an insignificant increasing trend or no trend.

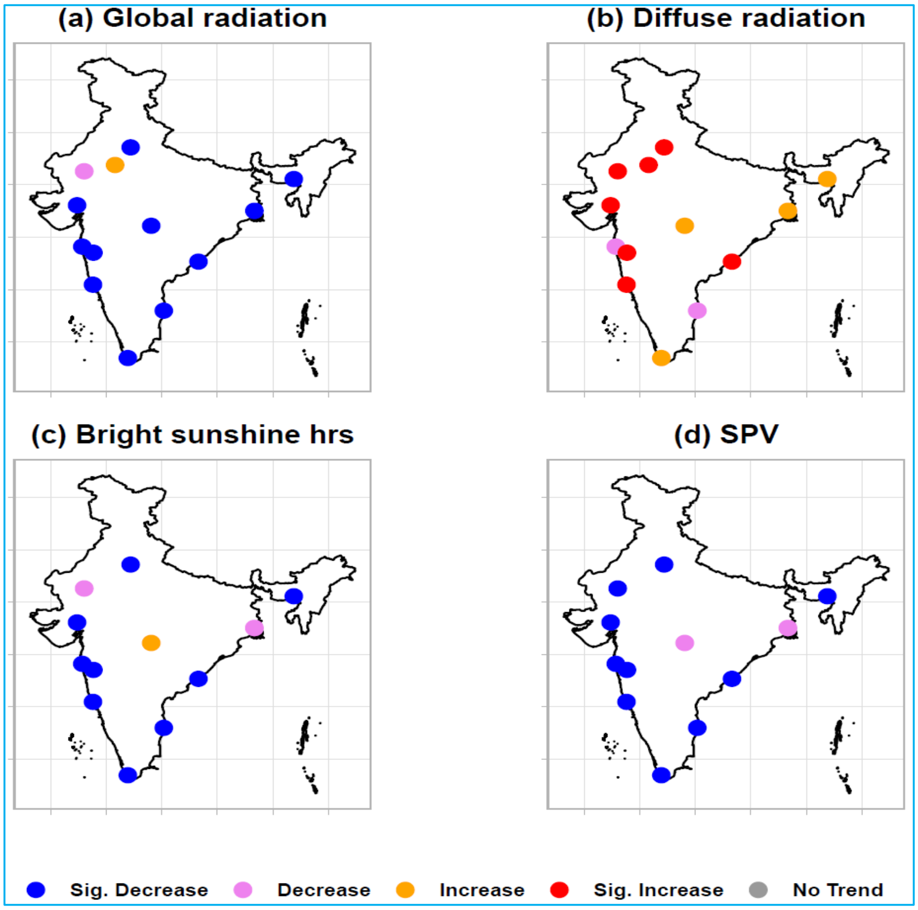
In June, only three stations (New Delhi, Shillong and Goa) have a significant decreasing trend (at 0.05 level). The stations such as Jodhpur, Ahmedabad, Pune, Visakhapatnam and Chennai have a statistically insignificant decreasing trend, whereas the stations such as Kolkata, Nagpur and Mumbai have an increasing trend which is statistically not significant. Thiruvananthapuram does not exhibit any trend during the month. However, all the stations exhibit a decreasing trend in the month of July, out of which, New Delhi, Ahmedabad, Pune and Goa have significant trends (at 0.05 level). The trends are statistically insignificant for the remaining stations. In August, only two stations (Jodhpur and Thiruvananthapuram) have a significant decreasing trend (at 0.05 level). Most of the other stations (New Delhi, Ahmedabad, Kolkata, Nagpur, Visakhapatnam and Goa) have decreasing trend which is statistically insignificant. The stations Shillong, Pune, Chennai and Mumbai have increasing trend in which the trend over Mumbai is significant (at 0.05 level) whereas the trends over the other stations are insignificant. Although, all the stations exhibit a decreasing trend in September. The stations such as New Delhi, Jodhpur, Pune, Visakhapatnam, Goa and Chennai have significant decreasing trend (at 0.05 level) whereas the remaining stations have a decreasing trend which are statistically not significant.

Nagpur has an increasing trend that is statistically not significant in all three months of post monsoon. In October, all other stations have decreasing trends; however, significant decreasing trend (at .05 level) is observed only in New Delhi, Kolkata, Mumbai, Pune, Goa and Thiruvananthapuram. In November, Visakhapatnam exhibit an increasing trend in addition to Nagpur, and all other stations exhibit a decreasing trend. However, only New Delhi, Jodhpur, Ahmedabad, Mumbai, Pune, Goa and Thiruvananthapuram have a significant decreasing trend (at 0.05 level) during the month. In December, all the stations except Ahmedabad (and Nagpur) have a significant decreasing trend (at 0.05 level). The decreasing trend over Ahmedabad is statistically not significant during the month.

3.9. *Monthly trend of technical potential for solar electricity generation*

Trend of SPV potential for different months is illustrated in Fig. 10 and Table 5. The trend pattern is almost homogeneous in all the months. SPV potential has decreasing trend in all stations during January-March. However, the decreasing trend is observed in more than 70% of the stations in other months.

In January, a significant decreasing trend in SPV potential (at 0.05 level) is observed over all the stations



Figs. 11(a-d). Annual trends of (a) global radiation (b) diffuse radiation (c) bright sunshine hours and (d) SPV potential during the period 1985-2019

except Shillong and Nagpur, where the trend is statistically not significant. Similarly, in February all stations exhibit a significant decreasing trend in SPV potential (at 0.05 level) except Jodhpur and Kolkata, where the trends are statistically insignificant.

A significant decreasing trend (at 0.05 level) is observed in all stations except Jodhpur and Nagpur in March, where these stations exhibit a statistically insignificant decreasing trend. In April, Jodhpur does not exhibit any trend, however, all remaining stations (except Nagpur) exhibit significant decreasing trends (at 0.05 level). SPV potential has a decreasing trend in Nagpur as well, however, the trend is statistically not significant. In the month of May, about 40% of the stations (New Delhi, Vishakhapatnam, Goa, Chennai and Thiruvananthapuram) exhibit a significant decreasing trend. Shillong, Ahmedabad and Kolkata exhibit decreasing trends in SPV whereas Mumbai exhibits an increasing trend, which are statistically not significant. Jodhpur, Nagpur and Pune do not exhibit any visible trend in SPV potential in May month.

The trend is inhomogeneous over the stations during the monsoon. In continuation with the trend pattern in the May, only about 40% of stations (New Delhi, Shillong, Ahmedabad, Goa and Chennai) exhibit a significant decreasing trend in SPV potential in June. Jodhpur, Pune and Vishakhapatnam have decreasing trends and Nagpur has an increasing trend during the month which are statistically not significant. Stations such as Kolkata, Mumbai and Thiruvananthapuram do not exhibit any visible trend in the month of June. All the stations except Jodhpur exhibit a decreasing trend in SPV potential in July, out of which New Delhi, Ahmedabad, Pune and Goa (Shillong, Kolkata, Nagpur, Mumbai, Vishakhapatnam, Chennai and Thiruvananthapuram) exhibit a significant (statistically not significant) decreasing trend; Jodhpur does not exhibit any visible trend in July. In August, New Delhi and Thiruvananthapuram exhibited a significant decreasing trend (at 0.05 level) whereas Jodhpur, Ahmedabad, Kolkata, Nagpur Vishakhapatnam and Goa exhibited decreasing trend which is statistically insignificant. Mumbai exhibits an increasing trend that is statistically not significant. However, Shillong, Pune and

Chennai do not exhibit any visible trend during the month. In September, Shillong does not exhibit any significant trend, whereas all the other stations except Kolkata and Nagpur exhibit a significant decreasing trend (at 0.05 level) in SPV potential. Kolkata and Nagpur also have a decreasing trend however, they are statistically not significant.

All stations have a decreasing trend in SPV potential in October, out of which New Delhi, Shillong, Ahmedabad, Kolkata, Pune, Goa and Thiruvananthapuram exhibit a significant trend (at 0.05 level). In November, Vishakhapatnam does not exhibit any trend. All the other stations except Nagpur and Chennai exhibit a significant decreasing trend (at 0.05 level) in SPV potential; the decreasing trend in Nagpur and Chennai are statistically not significant. All the stations except Nagpur have a significant decreasing trend in SPV potential in December; Nagpur does not exhibit any trend during the month.

Seasonal variation of the trend in SPV indicates that most of the stations have a significant decreasing trend in SPV potential for January-April and November-December. The trend is highly inhomogeneous for May-October. However, interestingly, New Delhi has a consistent significant decreasing trend in all the months.

3.10. *Annual trend of solar radiation, bright sunshine hours and SPV potential*

Fig. 11 provides a comprehensive picture of the annual trends of GR, DR, BHS and SPV potential over the country. A decreasing trend of GR, BHS and SPV potential and an increasing trend of DR in most of the stations is evident from the figure.

There is a significant decrease in the GR (at 0.05 level) in New Delhi, Shillong, Ahmedabad, Kolkata, Nagpur, Mumbai, Pune, Visakhapatnam, Goa, Chennai and Thiruvananthapuram. Among these stations, maximum decrease is observed over New Delhi (0.7%) and minimum decrease is observed over Pune (0.1%). Jodhpur has a decreasing trend that is statistically insignificant, and Jaipur has a statistically insignificant increasing trend in annual global radiation during the period. The decreasing trend in global radiation is attributed to the increase in high clouds and convective clouds (Wylie *et al*., 2005; Mishra, 2019). The high clouds and convective clouds increase the albedo and hence the incoming solar radiation reaching the earth's surface gets reduced (Mueller *et al*., 2011).

The trend of annual DR shows an increase in more than 80% of the stations, out of which nearly 60% of the stations exhibit a statistically significant increasing trend (at 0.05 level) and the remaining ~40% of the stations exhibit an increasing trend which are statistically insignificant. The increasing trend in diffuse radiation is attributed to the increase in atmospheric turbidity and cloudiness over the region (Bhattacharya *et al*., 1996; Singh and Kumar, 2016).

The trend in annual BHS shows a decreasing trend over the stations except for Nagpur, where there is an increasing trend but statistically not significant. However, a significant decreasing trend (at 0.05 level) is seen over New Delhi, Shillong, Ahmedabad, Mumbai, Pune, Visakhapatnam, Goa, Chennai and Thiruvananthapuram, and a statistically insignificant decreasing trend is observed over Jodhpur and Kolkata. The decreasing trend in BHS can be due to the increase in atmospheric turbidity and cloudiness over the region (Bhattacharya *et al*., 1996; Singh and Kumar, 2016). In line with the trends in GR and BHS, SPV also exhibits significant decreasing trends (at 0.05 level) in all the stations except Nagpur and Kolkata, where the decreasing trends are statistically not significant.

4. Conclusions

Understanding the climatology and trends of solar radiation and solar power potential are important in view of the emergence of solar power as an alternative to non-renewable energy resources. Further, a study of the global and diffuse radiations and the bright hours of sunshine using in-situ observations is also important in view of the regional variations in climate change and atmospheric pollution. In the present study, we report the climatology and trends of global and diffuse solar radiations, bright hours of sunshine and SPV potential for the period 1985-2019. Regional variations of these parameters during different months and the trends have been elucidated. Important results brought out from the study are given below.

(*i*) The GR over India is maximum over the northwest India and inland areas of peninsular India (200-260 Wm^{-2}) whereas it is minimum over the extreme north and northeast India (140-190 Wm^{-2}). All stations exhibit substantial monthly variation in GR. All stations except Srinagar exhibit maximum GR in pre-monsoon. Although, minimum GR is observed either in monsoon, post monsoon or winter depending upon the stations.

(*ii*) A significant reduction in GR (at 0.05 level) is noticed in all parts of the country except the extreme northwest, where the trend is not prominent. The reduction in GR is attributed to the increased atmospheric turbidity and cloudiness. However, the declining trend of the average GR over the country has been reduced in the recent decade.

(*iii*) DR is high over the coastal stations (97-105 Wm^{-2}) and minimum over Srinagar. The spatial pattern of DR over the inland region does not indicate any noticeable regional variations. High DR over the coastal stations is attributed to the high humidity and cloudiness over the stations. Maximum DR is observed in May or during the monsoon season, whereas the minimum is observed in either post monsoon or winter.

(*iv*) A significant increase in DR is observed in more than 50% of the stations, especially in the northwest and some parts of peninsular India. The increased atmospheric turbidity and cloudiness could be the primary cause for the same. The rate of increase of average DR over the country has escalated in the recent decade.

(*v*) Annual BHS is high in northwest India (7.7-8.5 hrs.) and low in north, northeast and southern peninsular India. Most of the stations exhibit maximum BHS during the pre-monsoon and minimum during the monsoon season. However, stations in north, northeast and southern peninsular India have different monthly variations.

(*vi*) BHS has significantly decreased in 75% of the selected stations. BHS decreased in other stations as well (except Nagpur where there is an increasing trend but that is statistically insignificant); however there the trends are statistically not significant.

(*vii*) India has good SPV potential in the range of 1800-3400 Wm^{-2} with substantial regional variations. High SPV potential (>3000 Wm^{-2}) is in northwest regions. Low SPV potential (<2000 Wm^{-2}) is mainly confined to north, northeast and southern peninsular India.

(*viii*) There is an alarming decreasing trend in the SPV in all the selected stations which is likely to continue in the near future as well. It would negatively impact energy production from solar resources. Wide use of solar panels with better efficiency will be needed to overcome this decreasing trend.

(*ix*) However, the main limitation of this study is the unavailability of continuous long-term datasets from many stations. The fidelity of the results can be improved by incorporating a greater number of stations and remote sensing datasets, which includes the future scope of the study.

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