Solar Radiation over Four Cities of India: Trend Analysis using Mann-Kendall Test

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Abstract- The present work deals with the study of the solar radiation trend over four major cities of India. The four cities Jodhpur, New Delhi, Nagpur, and Kolkata, represent different climate types: arid, semi-arid, sub-humid and humid, respectively. For trend analysis, we have used over forty years (1957/60-2003) global solar radiation (R_G) and thirty-one years (1973-2003) diffuse solar radiation (R_D) observational data. Based on the Mann-Kendall Test (MKT) a significant declining trend in R_G (solar dimming) has been observed at the all the stations at $p<0.05$ during 1957/60-2003. The decreasing trend in R_G in past decades indicates the increasing atmospheric load over the four cities of India. Maximum solar dimming has been observed over Jodhpur (-1.54 $Wm^{-2}y^{-1}$) for the period 1960-2003, followed by New Delhi (-0.98 $Wm^{-2}y^{-1}$, 1957-2003), Nagpur (-0.79 $Wm^{-2}y^{-1}$, 1960-2003), and Kolkata (-0.35 $Wm^{-2}y^{-1}$, 1957-2003). R_D has shown the increasing trend in all the station- Jodhpur (0.08 $Wm^{-2}y^{-1}$), New Delhi (0.05 $Wm^{-2}y^{-1}$), Nagpur (0.21 $Wm^{-2}y^{-1}$) and Kolkata (0.04 $Wm^{-2}y^{-1}$) for the period 1973-2003.The increase in R_D indirectly indicated the increase in the scattering of insolation by aerosols and clouds. However, in the later decades (after 1990s) R_G has shown significant increasing trend (solar brightening) in Jodhpur (1.14 $Wm^{-2}y^{-1}$) and New Delhi (2.24 $Wm^{-2}y^{-1}$) for the period 1991-2003.

Keywords-Diffuse solar radiation; global solar radiation;solar brightening, solar dimming, trend.

1. Introduction

The exchange of energy between the atmosphere and the earth's surface has been governed by solar radiation, which regulates the climate of our planet [1]. Any change in net available solar energy at the earth's surface will influence the monsoon patterns and dynamics that will further affect hydrosphere, atmosphere, lithosphere, and biosphere. The solar radiation information can act as an indicator of climate change since its availability on the earth depends upon the atmospheric load and sky conditions [2 and 3]. During the International Geophysical Year (1957/58) (IGY) people have realized the importance of solar radiation for our earth system processes. IGY led the measurement of solar radiation across the world [4, 5, and 6]. In India since late 1950s, R_G and R_D has been measured by the India Meteorological Department [7]. The measurements of solar radiation across the world have generated a large pool of solar radiation data (suitable for trend analysis). The trend analysis of solar radiation data has shown a declining trend over the earth's surface [4], from now on the decline in R_G termed as "solar dimming" in this paper. Several authors have reported varying rate of solar dimming per decade across the world like in Europe (-2.3%, 1971-1986) [8], Israel (-5%, 1954-1994) [9] and Ireland (-5%, 1954-1995) [10], in United States (-3%, 1961-1990) [11], in Asia, Hong

Kong (-10.6%, 1958-1992) [12], China (-2.5%, 1957-2000) [13], Japan (-0.8%, 1971-1989) [14], in African countries like Egypt (-6%, 1968-1994) [15], South Africa/Namibia (-2.2%, 1960-1990) [16], in Oceania, New Zealand (-3%, 1954-1990) [17], Arctic (-4%, 1950-1993) [12] and Antarctica (-2.3%, 1957-1994) [18]. The solar dimming continued till late 1980s/early 1990s, then in 1990s an increasing trend in solar radiation (global brightening) has been observed in many locations of the world. Like in European countries- Europe (1%, 1987-2002) [8], Germany (3.8%, 1985-2005) [4], Scandinavia (1.6%, 1985-2005) [4]. In North America- Continental United States (4.4%, 1995-2007) [19] and Oregon (1-2%, 1980-2007) [20]. In Asian countries – Japan (5%, 1990-2002) [4], China (2.7%, 1990-2002) [8], in Antarctica, South Pole (3.1%, 1992-2005) [4]. Over Indian region, the solar dimming has been observed [21, 22, and 23] (1981-2004).However, these studies have not supported global/solar brightening that was reported by [4]. The observational data used in the previous studies by [21 and 22] cover a wide region (12 stations) of India. However, they have not analyzed the trends of R_G before 1971. They have also used a linear regression method to test the significance of the trend in solar radiation. The data should be normally distributed for using linear regression method (parametric test). Several studies indicate that the solar radiation data for India is not normally distributed [24]. So, in this case, the use of non-parametric test like MKT is a good option for studying the trend in solar radiation. In the present study, we have analyzed the long-term data of R_G (1957/60-2003) and R_D (1973-2003) over four major cities of India (Jodhpur, New Delhi, Nagpur, and Kolkata). We have used the MKT to test the significance of the reported trends.

2. Study Region and Datasets

The geographical location of four stations of India- Jodhpur, New Delhi, Nagpur and Kolkata has been shown in Fig. 1.These stations represent four prime climates (arid, semi-arid, dry sub-humid and moist sub-humid) of India [25]. Jodhpur represents hot and arid climate and has the combination of both hill and valley terrain. This arid station has the higher amount of dust load in the ambient atmosphere. Another station, New Delhi represents the semi-arid climate type with very hot, dry summer (March-June) and cold winter (December to February). The climate of Nagpur is continental dry sub-humid. The climate of Nagpur is characterized by hot and dry pre-monsoon months (March - May), monsoon months (June-September), autumn (October - November) and winter (December - February). In Kolkata, summer is hot and humid. It has categorized as the moist sub-humid [25] based on moisture index. The climate of Kolkata is influenced by maritime disturbances. A moderate north westerly wind prevails for most of the year. The quality controlled data of R_G and R_D of the four stations (Jodhpur, New Delhi, Nagpur, and Kolkata) of India have been obtained from India Meteorological Department (IMD), Pune. R_G is measured with the pyranometer. In India, IMD, Pune is measuring R_G, and R_D since 1957 and all these data are calibrated time to time with World Radiometric References [21]. The absolute accuracy of the standard instruments is about ± 0.3% [21 and 22]. The accuracy of the instruments in the network is about ±1% [22]. Radiation data from 1960 to 2003 were used to study the trend of R_G over Jodhpur and Nagpur, and from 1957 to 2003, for New Delhi and Kolkata. However, only 31 years (1973-2003) R_D data have been used in the trend analysis.

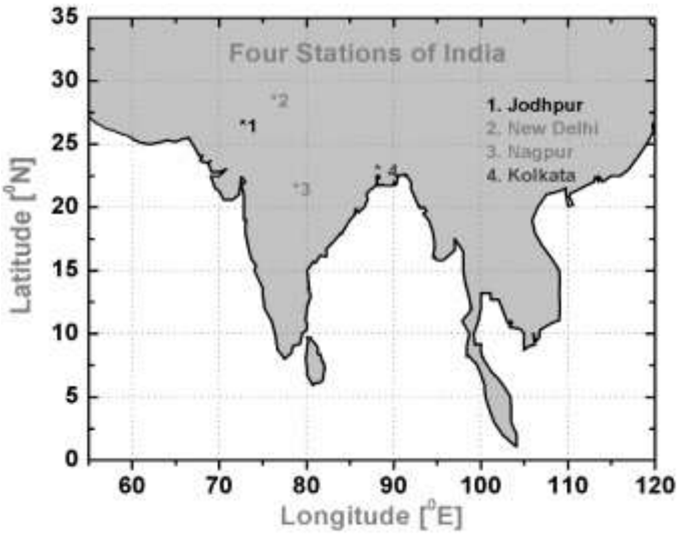

Fig. 1. Four stations of India used in the global (R_G) and diffuse solar radiation (R_D) trend analysis with latitude and longitude

3. Methodology

3.1. Data preparation

There were some gaps in radiation data. The gap in radiation data could be due to the damage caused to pyranometer domes by birds, very abrupt readings or some noise. For further analysis, we have filled the data gaps. To make the gap filling method simple and effective, we have used the long-term average method. The radiation data were available on a daily basis, so we have applied the gap filling method on a daily scale. To understand the applied gap filling procedure, let us consider we are having the data for the period 1970 -1975 and data for 1st January 1974 is missing. Then we have filled this day by taking the average of 1st January from 1970 -1975. We have analyzed the data properly where the values of solar radiation change abruptly (it was very less compared to previous years and later years) we have removed that data.

3.2.Binning of time series data

We have divided our time series data into three different "Bins" to check the validity of available facts about the solar dimming. In previous works [9] and [26] it has been shown that solar dimming has occurred till mid 1985-1990s and after that solar brightening [27] has occurred. However, for Indian stations, continual decrease in insolation has been observed [21 and 22].The complete time series data have been divided into three Bins: 1) complete time series (Bin 1), 2) time series up to 1990 (Bin 2) and, 3) time series from 1991 to 2003 (Bin 3).

3.3 Trend analysis

We have used the non-parametric MKT [28] to check the significance of the trends in solar radiation. It is a very good test for trend analysis (makes no assumption about the probability distribution of the time series data). However, here the relative magnitudes of sample data are more important than the original data values [29]. We have also used a linear regression to study the trend of R_G and R_D to compare it with MKT results We have calculated the slope (m) and its standard error (SE). The significance of the slope has been tested using "t-test" at the 95% level of significance ($p<0.05$).

4. Results

4.1. Seasonality in R_G and R_D

Monthly climatic means of R_G and R_D over the past decades, at the four stations are shown in Fig. 2 (a and b), along with the standard deviation (SD). Seasonal transitions were evident in R_G (Fig. 2a) and R_D (Fig. 2b). R_G was found to vary from 154 Wm^{-2} (December) to 243 Wm^{-2} (May) in Jodhpur, 138 Wm^{-2} (December) to 253 Wm^{-2} (April) in New Delhi, 154 Wm^{-2} (August) to 256 Wm^{-2} (April) in Nagpur, 153 Wm^{-2} (December) 238 Wm^{-2} (May) in Kolkata (Fig. 2a).

The seasonal change in R_G is due to the tilt of the earth's rotational axis. In the northern hemisphere, we see maximum (minimum)R_G in summer (winter) . However, in Nagpur during August (monsoon month) we have observed the minimum R_G . It might be due to the cloudy condition at this station during the monsoon month that was responsible for the depletion of R_G. Bimodal distribution in R_G was evident in all the three continental stations (Jodhpur, New Delhi, and Nagpur) with a primary peak in pre-monsoon and a secondary peak in the post-monsoon period. No sharp secondary peak was observed in the maritime station, Kolkata (Fig. 2a). The primary peak of R_G was highest in Nagpur during summer, followed by New Delhi, Jodhpur, and Kolkata. It has indicated the occurrence of clearer sky in Nagpur than Jodhpur (Fig. 2a). It is likely due to the arid condition in Jodhpur that leads to frequent dust storm events in pre-monsoon months [30]. R_G values in southwest monsoon season at all the stations were less most probably because of increased cloudiness [31] and this was also supported by high values of mean monthly R_D (Fig. 2b) in monsoon season in all the stations.

The contribution of R_D in R_G increases during monsoon months [32]. R_D has decreased rapidly in the post-monsoon and winter months in almost all the stations. R_D in winter and pre-monsoon were higher in New Delhi. In winter, it could be due to dense fog over New Delhi [33, 34, and 35] and in pre-monsoon there is an increase in absorbing aerosol load because of natural (desert dust) and anthropogenic (vehicular and industrial aerosols) sources [36].

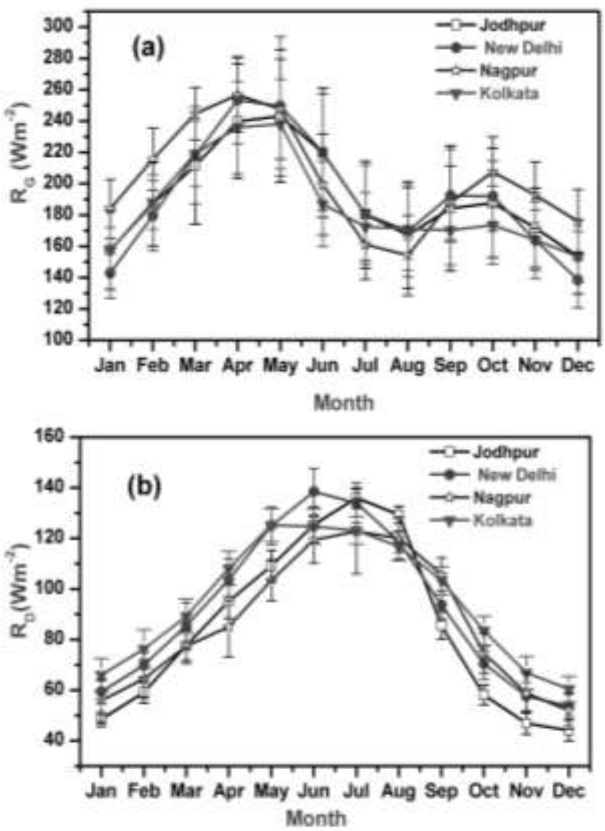

Fig. 2. Monthly mean climatology of global (R_G, Wm^{-2}) (1957/60-2003) (a) and diffuse solar radiation (R_D, Wm^{-2}) (1973-2003) (b) in Jodhpur, New Delhi, Nagpur and Kolkata. The bar indicates the standard deviation (SD) about the mean value.

4.2 Trends in R_G and R_D in Bin 1

The results of MKT trend analysis of R_G and R_D in all the three Bins (Bin 1, Bin 2 and Bin 3) over Jodhpur, New Delhi, Nagpur and Kolkata have been shown in Table 1. R_G trend line in Bin 1 has shown the negative slope in Jodhpur (-1.54 $Wm^{-2}y^{-1}$), New Delhi (-0.98 $Wm^{-2}y^{-1}$), Nagpur (-0.79 $Wm^{-2}y^{-1}$) and Kolkata (-0.35 $Wm^{-2}y^{-1}$). All these slopes are statistically significant at $p<0.05$ (Table 1). MKT analysis results statistics has also shown the significant decreasing trend at $p<0.05$ in R_G (1957/60-2003) at all the stations (Table 1). An overall decrease in R_G over all the stations in Bin 1 has supported the solar dimming over Indian region reported by [21, 22, and 23]. It was proposed that the two most probable causes of solar dimming be aerosols and clouds [26 and 9]. The natural (long range desert dust transport, forest fire, volcanic activity) and increase in anthropogenic activities like industrialization, vehicular pollution [37 and 38], and agricultural crop residue burning [39] has caused an increase in aerosol load in the atmosphere. In the present study also the annual mean of R_D in Bin 1, has shown positive slope 0.08 $Wm^{-2}y^{-1}$, 0.05 $Wm^{-2}y^{-1}$, 0.21 $Wm^{-2}y^{-1}$ and 0.04 $Wm^{-2}y^{-1}$ (Table 1.) in Jodhpur, New Delhi, Nagpur and Kolkata, respectively. Though it was only significant in Nagpur at $p<0.05$. The aerosols originating naturally (mineral dust) might be the reason for solar dimming in Jodhpur, which is located at the edge of the Thar desert and have sparse vegetation. The arid condition over this station could be causing the atmospheric regime to hold a maximum quantity of dust and sand [40]. From satellite images, it was confirmed that dust from Arabian countries is pushed by strong winds towards the Indian subcontinent [41]. The long-range transport of dust from Arabian countries increases the dust load over Jodhpur. During the pre-monsoon season, the concentration of dust aerosols is higher compared to other seasons [21]. In Jodhpur, we have found a maximum decline in R_G in pre-monsoon (-1.76 $Wm^{-2}y^{-1}$) (Table 1). However, the decline in R_G in pre-monsoon is not explained by R_D. New Delhi is the capital city of India, where developmental activities, industrialization, and unplanned urbanization have increased the air pollution. Even this place is also affected by the dust from the desert in the west. All these sources made this city one of the highly polluted cities of Asia. The air pollutants, particularly particulate matter and harmful gas concentration in New Delhi exceed the World Health Organization air quality guidance [42]. All these factors might be responsible for the declining trend of R_G in New Delhi in Bin 1 (Table 1). Here also the pre-monsoon season has contributed significantly in the solar dimming (-1.42 $Wm^{-2}y^{-1}$) followed by monsoon (-0.98 $Wm^{-2}y^{-1}$) (Table 1). It is quite interesting to note that in New Delhi, which is the part of Indo-Gangetic Plains (IGP) during winter the decline in R_G has been observed in all the Bins with maximum dimming in Bin 2 (-0.69 $Wm^{-2}y^{-1}$) followed by Bin 1 (-0.64 $Wm^{-2}y^{-1}$) and Bin 3 (0.3 $Wm^{-2}y^{-1}$) (Table 1). It could be associated with frequent inversions and dense fog [33 and 43] during winter. The anthropogenic activities are responsible for the building up of the black carbon and sulfate aerosols over IGP throughout the year [44 and 45]. These aerosols contribute to the formation of Atmospheric Brown Cloud, which block R_G [46]. The significant decreasing trend of annual R_G in Bin 1 in Nagpur indicates that the air pollution level has increased steadily in the city. Nagpur is the important city in Maharashtra present in the central part of the country and has a booming economy due to rapid industrial growth, urbanization and commercialization [47 and 21]. In 2001 census, the population of Nagpur has been recorded around 4.05 million [48]. The contribution of outdoor and indoor pollution increases the particulate matter in the atmosphere that interacts with the R_G. Nagpur has now emerged as a city that needs more effective implementation of environmental rules and regulation for decreasing the manifold increase in pollution [47]. Here on a seasonal scale during post-monsoon the maximum decline in R_G has been observed (-1.02 $Wm^{-2}y^{-1}$) followed by pre-monsoon (-0.74 $Wm^{-2}y^{-1}$) (Table 1). This decline in R_G could explain as aerosols build up slowly in the post-monsoon season, but they underwent hygroscopic growth when relative humidity >50% that leads to the high aerosol optical depth [49]. Kolkata, capital of West Bengal and was the first city developed by the British East India Company; they further made it their headquarters [50]. This city is also showing the aftermath of urbanization in terms of the increase in pollution. Around 1363 Km^2 area was under the urban land category during 1947-1990, and an increase 295 Km^2 (1990-2000) make the total area of urban land cover area around 1658 Km^2 [51]. Many industries were also established in Kolkata to satisfy the demand of a growing population. Eventually, air quality got severely affected by the loading of the atmospheric pollutants. The increase in the total number of vehicles in the city has also contributed significantly to the increase in pollution [52]. These all existing polluting factors have served a very important cause for solar dimming in this maritime station. In Bin 1, the contribution of winter (-0.55 $Wm^{-2}y^{-1}$) in declining of R_G was more than any other season followed by post monsoon (-0.38 $Wm^{-2}y^{-1}$). This city is the gateway for air pollutants from IGP to the Bay of Bengal during winter and post monsoon. During winter and post-monsoon, the prevailing wind pattern is mostly north westerly that brings the air masses from the most polluted region of IGP [53]. In winter, air pollutants cannot disperse easily because of low wind speed and inversions [54]. Frequent inversions hinder the dispersion of the air pollutants that causes them to concentrate near the surface and to reduce the amount of solar radiations reaching the earth's surface. Based on MKT, R_D has shown a significant increasing trend in winter season of 0.21 $Wm^{-2}y^{-1}$ and post monsoon 0.20 $Wm^{-2}y^{-1}$at $p<0.05$ (Table 1).

4.3 Trends in R_G and R_D in Bin 2 and Bin 3

The next question at this stage was whether the concept solar brightening after 1990s given by [4] holds for Indian region or not? The trend analysis of the bifurcated complete time series data in Bin 2 and Bin 3 has answered the above question. In Bin 2, significant decreasing trend in R_G was apparent in Jodhpur and New Delhi on annual and seasonal scale at $p<0.05$ (Table 1). The significant decline of R_G during the monsoon season over both the stations might be due to the aerosol indirect effect and cloud absorption [22].Nagpur has also shown the same declining trend in R_G on annual and seasonal scale except the monsoon (Table 1) in Bin 2. This indicates that over Nagpur the monsoon has least contribution to R_G decline. It might be due to the rain washout effect over Nagpur during the monsoon season that decreases the atmospheric load. Nagpur was the only station where the increasing trend in R_D was statistically significant on annual and in all seasons at $p<0.05$ based on MKT (Bin 2). This has raised the issue of increasing atmospheric pollution over this city. In Kolkata, only winter has shown a significant decline in R_G (-0.36 $Wm^{-2}y^{-1}$) in Bin 2. The significant contribution of only winter might be the reason for the least decline in R_G on an annual scale. In Bin 3, a significant increase in R_G trend has been observed in Jodhpur (1.14 $Wm^{-2}y^{-1}$) at $p<0.05$. The monsoon (2.51 Wm-

Table 1. Slope (m) ($Wm^{-2}y^{-1}$), Standard Error (SE) and Mann Kendall Trend (MKT) of global (R_G) and diffuse solar radiation (R_D) in the four stations (Jodhpur, New Delhi, Nagpur and Kolkata) of India on annual and seasonal scale in Bin 1 (1957/60-2003), Bin 2 (1957/60-1990) and Bin 3 (1990-2003). The 'm' significant at $p<0.05$ represented with superscript 's '. The letter 'D' and 'I' represents the significant decreasing and increasing trend (MKT) at the $p<0.05$, respectively. 'N' represents the non-significant trend at $p>0.05$.

	Bin1						**Bin2**						**Bin3**					
	R_G			R_D			R_G			R_D			R_G			R_D		
	m	**SE**	**Trend**	**m**	**SE**	**Trend**	**m**	**SE**	**Trend**	**m**	**SE**	**Trend**	**m**	**SE**	**Trend**	**m**	**SE**	**Trend**
Jodhpur																		
Annual	-1.54 ^{s}	0.21	D	0.08	0.05	N	-2.16 ^{s}	0.34	D	0.09	0.10	N	1.14	0.69	I	-0.17	0.19	N
Winter	-1.05 ^{s}	0.19	D	0.07	0.05	N	-1.26 ^{s}	0.36	D	0.09	0.09	N	-0.57	0.57	N	-0.61 ^{s}	0.16	N
Pre-Monsoon	-1.76 ^{s}	0.33	D	-0.07	0.10	N	-2.68 ^{s}	0.59	D	0.18	0.23	N	1.46	1.11	N	-0.27	0.40	N
Monsoon	-1.66 ^{s}	0.31	D	0.14 ^{s}	0.06	I	-2.68 ^{s}	0.51	D	0.05	0.13	N	2.51 ^{s}	1.01	I	0.21	0.20	N
Post Monsoon	-1.46 ^{s}	0.27	D	0.21 ^{s}	0.06	I	-1.90 ^{s}	0.49	D	0.06	0.14	N	0.45	1.16	N	-0.10	0.20	N
New Delhi																		
Annual	-0.98 ^{s}	0.15	D	0.05	0.06	N	-1.10 ^{s}	0.24	D	0.32 ^{s}	0.13	I	2.24 ^{s}	0.62	I	-0.13	0.23	N
Winter	-0.64 ^{s}	0.12	D	0.15 ^{s}	0.07	I	-0.69 ^{s}	0.22	D	0.33	0.17	I	-0.37	0.52	N	-0.19	0.20	N
Pre-Monsoon	-1.42 ^{s}	0.25	D	0.09	0.14	N	-1.45 ^{s}	0.32	D	0.15	0.24	N	4.04	1.94	I	-0.29	0.67	N
Monsoon	-0.98 ^{s}	0.24	D	0.01	0.07	N	-1.22 ^{s}	0.39	D	0.38	0.18	N	3.49 ^{s}	1.14	I	0.04	0.15	N
Post Monsoon	-0.83 ^{s}	0.14	D	0.20 ^{s}	0.09	I	-0.98 ^{s}	0.22	D	0.43 ^{s}	0.20	I	0.89	0.86	N	-0.13	0.38	N
Nagpur																		
Annual	-0.79 ^{s}	0.13	D	0.21 ^{s}	0.08	I	-0.79 ^{s}	0.24	D	0.64 ^{s}	0.13	I	-0.14	0.67	N	-0.15	0.34	N
Winter	-0.74 ^{s}	0.12	D	0.35 ^{s}	0.09	I	-0.83 ^{s}	0.21	D	0.65 ^{s}	0.19	I	-0.34	0.79	N	-0.34	0.32	N
Pre-Monsoon	-0.85 ^{s}	0.21	D	0.31 ^{s}	0.11	I	-0.92 ^{s}	0.39	D	0.79 ^{s}	0.23	I	-0.49	1.04	N	0	0.44	N
Monsoon	-0.68	0.21	D	-0.04	0.13	N	-0.58	0.37	*N*	0.59 ^{s}	0.22	I	0.14	1.37	N	-0.09	0.52	N
Post Monsoon	-1.02	0.15	D	0.39 ^{s}	0.12	I	-0.96 ^{s}	0.28	D	0.49 ^{s}	0.18	I	0.10	0.79	N	-0.17	0.56	N
Kolkata																		
Annual	-0.35 ^{s}	0.12	D	0.04	0.09	N	-0.23	0.22	N	0.00	0.16	N	-0.78 ^{s}	-0.30	D	-0.54	0.36	N
Winter	-0.55 ^{s}	0.10	D	0.21 ^{s}	0.10	I	-0.36 ^{s}	0.18	D	0.37 ^{s}	0.18	I	-0.91	0.53	D	-0.77	0.38	D
Pre-Monsoon	-0.33	0.24	D	0.12	0.10	N	-0.34	0.45	N	-0.14	0.24	N	-1.57 ^{s}	0.59	D	-0.02	0.37	N
Monsoon	-0.05	0.20	N	-0.21	0.14	N	-0.01	0.37	N	-0.15	0.23	N	-0.48	-0.61	N	-0.77	0.69	D
Post Monsoon	-0.38	0.24	D	0.20	0.10	I	-0.31	0.46	N	-0.04	0.21	N	-0.02	0.57	N	-0.51	0.34	D

$^{2}y^{-1}$) and pre-monsoon (1.46 $Wm^{-2}y^{-1}$) season have a major contribution to R_G increase (Table 1). This shows that there must be a significant decrease in aerosols indirect effect. The overall increase in R_G would be likely due to a decrease in natural aerosol load close to Jodhpur. The rainfall in Jodhpur has increased in recent decades [55] that cause the dust to settle down and decrease its concentration in the atmosphere. The Indira Gandhi Canal (now Rajasthan canal) in Rajasthan was built with the aim of converting semi-arid and arid desert wastelands into croplands [56]. This irrigation canal has increased the water availability in this arid region [57]. The water supply in this city increases the prospects for better water management. Day by day, Jodhpur is becoming greener as water is now being used for the plantation of tree [58] .The plants and tree leaves act as a scavenger and provides a surface for settling the dust. Even in Bin 3 R_D has shown the negative slopes on annual and seasonal scales except monsoon season in Jodhpur (Table 1). The increase in rainfall might be because of the increase in precipitation efficiency of clouds. Like Jodhpur, New Delhi has also shown a significant increasing trend of 2.24 $Wm^{-2}y^{-1}$ (annual) in R_G in Bin 3. The maximum increase in R_G has been found in pre-monsoon (4.04 $Wm^{-2}y^{-1}$) season followed by the monsoon season (3.49 $Wm^{-2}y^{-1}$). The significant increase in R_G might be due to a decrease in aerosol concentration or clearer sky conditions over the capital city of India. The Central Pollution Control Board (CPCB) suggested that the level of suspended particles has been stabilized or even fallen over this city [59].The reduction in aerosols might also lead to the reduction of aerosol direct effect in pre-monsoon season and aerosol indirect effect and cloud absorption in the monsoon season. The reason for the decrease in aerosol concentration over New Delhi could be associated with effective environmental pollution control in the later decades. Over New Delhi, intensive, environmentally sound practices adopted after 1990s [60] and replacement of Diesel buses with CNG buses in early 2000 was a breakthrough in this direction. A significant decline in the concentration of CO, SO2 and PAHs [61] and marginal fall in SPM and PM10 [62] has been observed after implementing CNG as a fuel in vehicles. After 1990s, the government of India has taken many initiatives to control the air pollution that might be solely responsible for increasing the R_G in New Delhi in later decades (Bin 3). However, in winter we have observed the negative slope in R_G (Table 1). Although we cannot ignore the decrease in the rate of solar dimming in winter in Bin 3 (-0.37 $Wm^{-2}y^{-1}$) compared to Bin 1 (-0.64 $Wm^{-2}y^{-1}$) and Bin 2 (-0.69 $Wm^{-2}y^{-1}$). The cause of the decreasing rate of R_G decline during the winter could be attributed to the improvement in the environmental condition. In Nagpur, we have not seen any significant increase or decrease in R_G and R_D on annual and seasonal scale (Table 1). However, positive slope has been observed in monsoon (0.10 $Wm^{-2}y^{-1}$) and post-monsoon (0.14 $Wm^{-2}y^{-1}$) in Nagpur. In Kolkata R_G decline significantly at the rate of -0.78 $Wm^{-2}y^{-1}$ on an annual scale (Bin 3). On a seasonal scale, the decline in R_G was maximum (significant) in pre-monsoon (-1.57 $Wm^{-2}y^{-1}$) and negative slope is reported winter (-0.91 $Wm^{-2}y^{-1}$), monsoon (-0.61 $Wm^{-2}y^{-1}$) and post-monsoon (-0.02 $Wm^{-2}y^{-1}$) (Bin 3). . In Kolkata, the percentage of R_D in R_G is about 51% (not shown). According to [21] the spatial and temporal pattern of R_D is complex and inhomogeneous. In this study, they have found highly significant increasing trend in R_D in many stations. However, a significant trend in R_G was not observed at those stations. So only based on R_D it is not always possible to explain the trends in R_G completely. We need to consider some other important factor like atmospheric turbidity for explaining the trends in R_G. R_G anomalies (deviation from 1957/1960-2003 mean) and R_D anomalies (deviation from 1973-2003 mean) is shown in Fig. 3 and Fig. 4, respectively.

The values of R_G and R_D Jodhpur deviated more in Jodhpur (Fig. 3 (a)) and Nagpur (Fig. 4 (c)) from the mean. The more fluctuation in R_G might be due to the fact that local environment of Jodhpur is very much influenced by the Thar Desert [63]. In Bin 1 and Bin 2, all stations have shown the negative slopes. In Fig. 4, increasing trend in R_D has explained the declining trend in R_G in Bin 1 and Bin 2. Here also in Bin 3 only Jodhpur (Fig. 4a) and New Delhi (Fig. 4b) have shown an increasing trend. MKT is the better statistical test for checking the significance of trends compared to simple linear regression. Linear regression sometimes fails to detect the actual significant trends ; however MKT is robust and can able to catch the significant l trends.

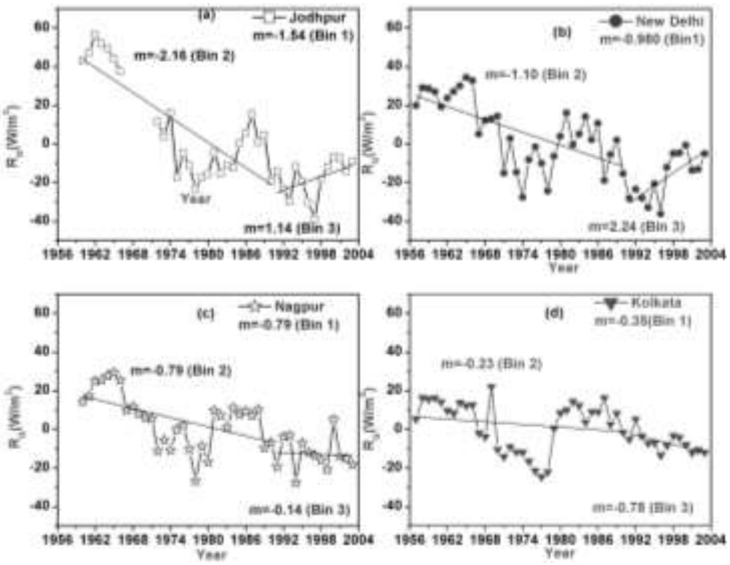

Fig. 3. The global solar radiation (R_G, Wm^{-2})anomalies (deviation from 1957/1960-2003 mean) in Jodhpur (a), New Delhi (b), Nagpur (c) and Kolkata (d). Slope (m) in Bin 1, Bin 2 and Bin 3

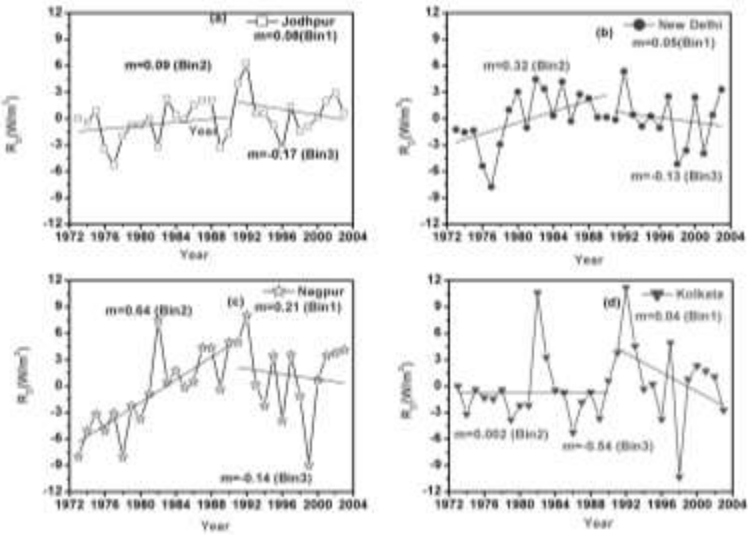

Fig. 4. The diffuse solar radiation (R_D, Wm^{-2})anomalies (deviation from 1973-2003 mean) in Jodhpur (a), New Delhi (b), Nagpur (c) and Kolkata (d). Slope (m) in Bin 1, Bin 2 and Bin 3

5. Conclusions

In the present work, the solar radiation trend over the four stations (Jodhpur, New Delhi, Nagpur, and Kolkata) representing different climate types (arid, semi-arid, dry sub-humid, and moist sub-humid, respectively) has been studied. *In situ* data of R_G and R_D from IMD, Pune have been used for the study. Data from 1957/60 -2003 has been divided into the three Bins. The Bin 1, represents the data of the complete period (1950s-2000); Bin 2 represents the early decades (before1990s), and Bin 3 (after 1990s) represents the later decades. In all the four stations of India, declining trend were significant at $p<0.05$ in Bin 1. Decline in R_G was maximum in Jodhpur (-1.54 $Wm^{-2}y^{-1}$) followed by New Delhi (-0.98 $Wm^{-2}y^{-1}$), Nagpur (-0.79 $Wm^{-2}y^{-1}$) and Kolkata (-0.35 $Wm^{-2}y^{-1}$). On a seasonal scale also the significant declining trend in R_G has been observed. In Jodhpur and New Delhi pre-monsoon season played the significant role in the decline of R_G where the decline in R_G was -1.76 $Wm^{-2}y^{-1}$and -1.42 $Wm^{-2}y^{-1}$, respectively. However, in Nagpur and Kolkata the post monsoon (-1.02 $Wm^{-2}y^{-1}$) and winter (-0.55 $Wm^{-2}y^{-1}$). In many parts of the world increasing trend has been observed in mid-1980s or after 1990s. In Bin 3, Jodhpur and New Delhi have also shown positive slopes of 1.14 $Wm^{-2}y^{-1}$ and 2.24 $Wm^{-2}y^{-1}$, respectively. R_G in Kolkata has shown significant declining trend (-0.78 $Wm^{-2}y^{-1}$) in Bin 3. However, Nagpur has not shown any significant trend at p=0. 05. From *in situ* data, it has been confirmed that solar dimming took place over the four stations of India in the past decades supporting the globally occurring solar dimming. The solar brightening has been also detected in the two stations (Jodhpur and New Delhi). The improvement in environmental condition has caused a significant increase in insolation at the earth's surface. Thus, now it is confirmed that solar dimming has occured globally and Indian region is not immune to it.. However, the solar brightening has occured where there was the improvement in air quality. The places where environmental degradation has been checked using strict environmental rules and regulation, improvement in air quality has been observed. More detailed analysis of solar radiation over other stations of India is also required to understand the solar radiation trend over Indian subtropics. The present study also presented the importance of MKT for trend analysis.

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