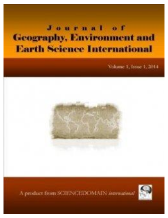

Journal of Geography, Environment and Earth Science International

19(2): 1-15, 2019; Article no.JGEESI.47487
ISSN: 2454-7352

Analysis of Direct, Diffuse and Global Solar Radiations over Varanasi at Eastern Indo-Gangetic Plain (IGP), India

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Authors' contributions

This work was carried out in collaboration between all authors. Authors PKY, MKS and SV designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors PKY and PG managed the analyses of the study. Authors RKS and DPY managed the literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JGEESI/2019/v19i230081
Editor(s):
(1) Dr. Kaveh Ostad-Ali-Askari, Department of Civil Engineering, Isfahan (Khorasgan) Branch, Islamic Azad University, Isfahan, Iran.
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Reviewers:
(1) Bankole Adebanji, Ekiti State University, Nigeria.
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(3) Romdhane Ben Slama, University of Gabes, Tunisia.
(4) Branko Vukovic, University of Osijek, Croatia.
Complete Peer review History: http://www.sdiarticle3.com/review-history/47487

Original Research Article

Received 23 October 2018
Accepted 11 February 2019
Published 23 February 2019

ABSTRACT

The paper presents the seasonal solar radiations over Varanasi (25°20' N, 83° 00' E 81.1m altitude) in Eastern Uttar Pradesh (UP) in India. An investigation on solar radiation over Varanasi station, India is carried out by using the five years (2010-2014) recorded direct, diffuse, and global radiations data obtained from the radiation unit installed by India Meteorological Department (IMD) at Banaras Hindu University (BHU) campus. Analyses of winter (December, January, and February), summer (March, April, and May), monsoon season (June, July, August, September),

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and post monsoon (October, November) period shows that diffuse solar radiation is maximum (~1.42 MJ/m^2) during monsoon season in 2012 at 12:00 IST and global solar radiation is maximum (~2.9 MJ/m^2) during summer season in 2012 at 13:00 IST. The results of solar radiation are further analyzed with the aerosols optical depth over Varanasi. The increase in diffuse radiation are found to be well correlated (R= 0.67) with higher values of aerosols optical depth during summer over Varanasi.

Keywords: Solar radiation; scattering; diffusion; temperature; AOD.

1. INTRODUCTION

Solar radiation is the most important part of Earth-Sun relationship. It is the main driving force of the atmospheric circulation. Passing through the atmosphere, solar radiation gets attenuated due to scattering, diffusion, absorption, and reflection by atmospheric composition [1]. However, there are various atmospheric conditions that cause changes in solar radiation and perturb its intensity. Presence of aerosols atmospheric water vapor content, distributions of cloud cover, etc. causes major changes in the incoming solar radiation properties, and dev elop conditions through which the amount of solar radiation varies on spatial as well as temporal scales. Solar radiation is the primary energy source to the earth's surface [2], and ultimately controls the life and ecosystems, by playing with the hydrological cycle, weather and climate, surface energy budget, the diurnal/ seasonal thermal regime, and the health of biota, including flora and fauna. Studies accomplished so far have identified that the solar radiation is not a stable quantity, rather it significantly vary on decadal time scale due to various long-term as well as short-term causes, e.g. sunspot cycle [3] natural or anthropogenic pollution, cloud cover [4] cloud microphysical properties [5].

On the basis of long term studies done with a view of solar dimming or brightening [6] concept have shown that solar radiation is decreasing from 1960s to 1980s, which recovered afterwards. Solar radiation shows variability from one region to another region, mainly caused due to changes in cloud optical depth [7], cloud cover and soil properties [8], as well as aerosols number concentration. Studies show that the cause of increase in aerosol concentration in the atmosphere is found to be more pronounced in developing and densely-populated countries, such as India, and it is comparatively low in cases of developed part of the globe, where air quality regulations are stricter. Although, the importance of changes in solar radiation is directly or indirectly affecting the day-to-day life of the human being [9], studies on solar radiation is scanty over many parts of the globe, including Indian region. Striking reduction in solar radiation are found over India which is related with the increased particle density, caused by industrial pollution, vehicular pollution, biomass burning and soil-dust mixing in the atmosphere. The decrease in solar radiation over India was found to be almost doubled during cloudy days than the clear-sky conditions. The decrease rate, however, is different for various regions and seasons.

Studies also revealed that solar radiations are not constant but changes spatially and seasonally. These changes are mostly natural due to rotation and revolution of the earth, but role of intermittent natural (e.g. volcanoes, dust storms) [10] or man-made (e.g. land use land cover change, agriculture residue burning) [11] processes over specific region can not be ruled out. Many locations around the world have already reported a widespread decreasing trend in global solar radiation [12,13,14,15,16,17,18, 19,20,21]. For India also, the decreasing trend is reported by Ramanathan [22]. After 1990, however, some evidences have been found to show an increasing trend [23,24], but they are for specific regions only. The major sources of these trends have been related to the change in aerosols, clouds, or both, for the region of concern, where aerosols got more attention ([25]. The study [26]) have reported that monthly mean global solar radiation over India is decreasing at the rate of about 0.86 MJ/m^2 per year for the period 1981–2004. The rapid industrialization and urbanization in India, after 1990, with its increased socio-economics, has caused tremendous increase in energy demand, leading to increase in the emission of pollutants and aerosols. The atmospheric pollution, in general, has significantly increased since 1990s [27]. Further, high level of pollutants in the Indo-Gangetic plain is reported by many authors, who related this increased aerosol concentration due to land use changes, biomass burning, vehicular pollution, etc.

Although, global radiation has been studied in detail for many parts of the world, the diffuse and direct components of solar radiation has not been studied in general, due to unavailability of datasets. Global observations, however, have shown a decreased diffuse radiation for Germany [28], Ireland [29] and parts of China [18]. Theoretically, the clear sky is effective for transmitting more of the solar beam, corresponding to more direct solar radiation, while a cloudy and or dusty sky is effective for more diffusion of solar light, corresponding to more diffuse radiation at the surface. This paper thus attempts to investigate the seasonal direct, diffuse and global solar radiations over Varanasi (25°20' N, 83°00' E 81.1 m altitude) in Eastern Uttar Pradesh (UP) in India.

2. METHODOLOGY

2.1 Solar Radiation (SR)

The solar radiation data for the year 2010-2014 has been obtained from Ozone Unit, Varanasi, which is run by IMD. The radiation data was taken by Thermoelectric Pyranometer, an automatic instrument designed to measure solar radiance flux density (MJ/m^2). The details of instrument have been given in section 3. All the solar radiation data has been checked manually, for consistency and they are categorized in to monthly basis. After initial quality check, the data is processed and the 10 minute data is added for each hour for final processing. 12 hour daytime data, extending from 0600 hours till 1800 hours (IST) has been considered to infer the diurnal information. The yearly variation of diurnal information is obtained by averaging all the days. Yearly average and summation of radiation data is developed from daily variation. Data was further divided into four seasons namely winter (December, January, February), summer (March, April, May), monsoon (June, July, August and September), and post monsoon (October and November) according to IMD criteria.

2.2 Aerosol Optical Depth (AOD)

In order to assess the particulate loading at IGPs for the monitoring period, Moderate resolution Imaging Spectrophotometer (MODIS) data on board Terra satellite were analyzed for Aerosol Optical Depth at 550 nm (AOD_{550}). We have used the level 2.0 collection version 5.1 Aerosol Optical Depth at 550 nm wavelength is extracted from MODIS satellite Terra platform for the study period [30,31].

3. STUDY AREA AND INSTRUMENTATION DETAILS

Varanasi (25°20' N, 83°00' E 81.1 m altitude) is one of the ancient and holy cities of the world. Due to its inherited population, and due to great number of floating population on daily basis, the city is one of the densely populated locations in Central Indo-Gangetic Plains (IGP). Since the soil of IGP is highly fertile, agriculture is one of the major livelihood of this region and, hence, solar radiation is one of the most important atmospheric factor for this region. The average temperature and average precipitation, remains around 26.1°C and 998 mm, respectively.

The radiation data for the Varanasi has been obtained from a pyranometer radiation table installed by IMD at the roof top of a 15 meter building, and it runs under the Ozone Unit set up. The place of the table is devoid of any hindrance from all the directions. The solar radiation data measured under all sky conditions have been collected from this radiation table comprised of direct, diffuse, and global solar radiation. The 2010-2014 data set was taken by Thermoelectric Pyrometer on a planer surface, and it is designed to measure solar radiance flux density from the hemisphere with wavelength ranging from 300 nm to 3000 nm. For this instrument, there is no response obtained when the sun is at horizon. The radiation data obtained using automatic logger at each second is collected as average of the radiation at each minute. This minute data is, then, added for each 10 minute intervals for collection of long term record.

4. RESULTS AND DISCUSSION

Global solar radiation can be defined as addition of direct and diffuse component of solar radiation [32]. The solar radiation consist mainly of two component: Direct and diffuse component. Diffuse radiation comes from all the directions, while direct radiation follows the path of sun throughout the day. The transmission of radiation through the atmosphere is affected by aerosol, water vapor, gases and clouds. In an ideal scenario, the global radiation informs about the widespread available radiation in the atmosphere. When there are more number of light diffusing agents (aerosols and other particles) in the atmosphere, the diffuse radiation shall be more.

Seasonally averaged diurnal, global, diffuse and direct solar radiation, as obtained for five years of data, are shown in Fig. 1 (a: winter, b: summer, c: monsoon and d: post-monsoon).

4.1 Annual Variation of Solar Radiation

The Fig. 1(a) shows that diffuse and global solar radiation is very low during the sunrise and sunset time and it is showing a usual bell-shaped diurnal distribution, however, the direct radiation is varying according to solar activity. For the 2010-2014 data, winter season global solar radiation is found to be maximum (2.15 MJ/m^2) at 12 IST during 2013 and minimum (0.02 MJ/m^2) at 7 IST during 2013, respectively. Direct solar radaiation was maximum (0.87 MJ/m^2) at 8 IST during 2013 and minimum was 0.31 MJ/m^2 at 19 IST in 2014. The diffuse solar radiation maximum was found to be 1.02 MJ/m^2 at 13 IST in 2014 and minimum was 0.03 MJ/m^2 at 7 IST in 2011.

Fig. 1(b) represent the direct, diffuse and global solar radiation over Varanasi, during summer season. Fig. 1 b shows that the maximum global solar radation was found to be 2.9 MJ/m^2 at 12 IST in 2010 and minimum was 0.23 MJ/m^2 at 18 IST in 2014. Maximum diffuse solar radiation was found to be 1.0 MJ/m^2 at 12 IST in 2013 and minimum was 0.20 MJ/m^2 at 17 IST in 2014. Maximum direct solar radiation was found to be 1.07 MJ/m^2 at 16 IST in 2014 and minimum was 0.43 MJ/m^2 at 9 IST in 2010. In comparision of direct and diffuse radiation, the diffuse radiation was more in summer season. In 2011, as there was more number of light diffusing agent (dust partical and aerosols) in the medium, so, the diffuse radiation was more in comparision to direct radiation. Dust particles may also act as absorbing agents causing a reduction in the direct radiation.

Fig.1(c) shows such relationship from the five years (2010-2014) during the monsoon season. The maximum global solar radiation was found to be 2.57 MJ/m² at 11 IST.in 2014 and minimum was 0.07 MJ/m² at 18 IST. in 2014. The maximum direct solar radiation was found to be 0.84 MJ/m² at 15 IST in 2011 and minimum was 0.34 MJ/m² at 10 IST in 2013. Maximum diffuse solar radiation was found to be 1.42 MJ/m² at 12 IST in 2012 and minimum was 0.29 MJ/m² at 18 IST in 2011.

Fig.1(d) shows a fairly smooth relationship yearly global, direct and diffuse solar radiation for each of five years. Fig. shows that the maximum global solar radiation during the post monsoon season was found to be 2.23 MJ/m² at 13 IST in 2012 and minimum was 0.04 MJ/m² at 7 IST in 2012. The maximum direct radiation was found to be 1.16 MJ/m² at 15 IST in 2011 and minimum was 0.25 MJ/m² at 8 IST in 2014. Maximum diffuse solar radiation was found to be 1.12 MJ/m²at 12 IST in 2010 and minimum was 0.05 MJ/m² at 18 IST in 2011.

Fig. 2 shows the range in direct, diffuse and global solar radiation values for 2010-2014 during the winter, summer, monsoon and post monsoon seasons, respectively. The global solar radiation was found to be increasing. Fig 2(b) shows that the maximum global solar radiation during summer season is observed during 2010 due to fewer amounts of water vapor, soot particle and burning of fossil fuel present in the atmosphere. The boxes marks the 25 and 75% quartile while whisker gives the maximum and minimum value. In winter season, diffuse solar radiation was less than the direct and global. Fig. [2(a)] shows that less particle or scattering agent present in the atmoshpere, so, the diffuse radiation was less in winter season. In summer and monsoon season, diffuse solar radiation was high in comparasion to direct radiation [Fig. 2(b-c)]. Diffuse radiation is formed by scattering of the direct beam by particles in the atmosphere. Diffuse solar radiation shows higher value in summer and monsoon season due to increased turbidity and cloudiness during this period. Cloudiness is having the greatest influence on diffuse radiation in monsoon season. During July month (rainy season), sunshine hours are found to be less at Varanasi. In general, during summer months, the diffuse component of radiation increases and the direct component decreases, however, an increase in diffuse radiation in winter when precipitation is generally low, was a result of increased optical density pattern from the particles from extensive burning of fossil fuels in the region [33].

Fig. 3 shows the aerosol optical depth with increasing trend of diffuse radiation data for the period of study. The annual average daily diffuse solar radiation is observed to be the highest for the month of June, 2013 (0.78 MJ/m²/day). The annual average daily aerosol optical depth is found to be highest during September, 2013 (0.67) while it is lowest (0.52) during October, 2014. The trends in annual means of diffuse radiation and aerosol optical depth have also been analyzed in the study (Fig. 3 and Table 1). The linear trends for diffuse radiation during the period 2010 – 2014 over Varanasi are found to be increasing.

Annual maximum and minimun temperature during 2010-2014 are shown in Table 2. The annual average maximum temperature show decreasing trend with a negative slope of -0.048. The solar radiation affect the T_{max} more than T_{min} [23]. During the 2010 to 2014, the change in T_{max} for summer season, however, increased from 45 to 47°C. higher aerosol optical depth value as well as change in cloud properties contribute to this difference [26].

4.2 Relationship between AOD and Solar Radiation

The AOD observations (2010-2014) from MODIS satelite data have been analysed in explaining the trends in global radiation over Varanasi. Solar irradiance is known to be correlated with cloud cover and bright sunshine duration. The most probable causes of trends in solar radiation is a change in the amount of cloud cover [17].

Fig. 4 represents the seasonal variation indiffuse radiation and aerosol optical depth. It is seen that there is an increasing trend in aerosol optical depth with diffuse solar radiation with higher values during 2013. Since increase in the cloud amount decreases the direct solar radiation and augments diffuse sky radiation [34,35,36], we choose 2013 to conduct further analysis to find relation between diffuse solar radiation and aerosol optical depth.

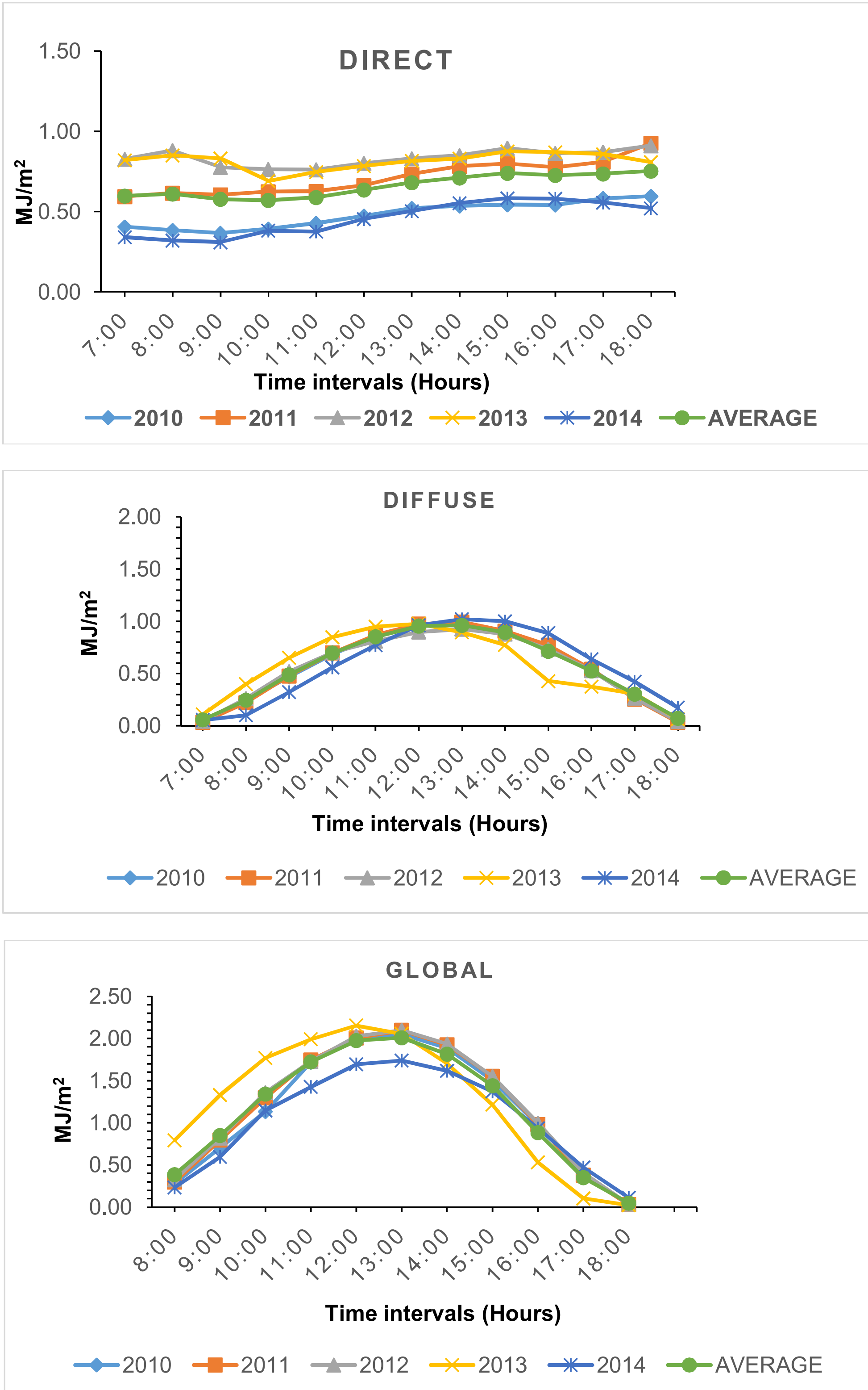
Relationship between difffuse solar radiation and AOD is shown in Fig. 5 which indicate increasing trend due to increase in the AOD with a positive slope of 0.0371. The correlation between AOD and diffuse solar radiation is found to be more during summer (0.67) than that of winter over Varanasi. Due to the high population growth, increasing urbanisation, industrialisation, the AOD over the IGPs is found to be increasing and hence the diffuse solar radiation also increases because of diffuse solar radiation component are influenced by an increament or decrement of AOD.

Table 1. The observed solar radiation for annual, winter, summer, monsoon and post-monsoon seasons averaged for the period 2010 – 2014 over Varanasi

Seasons	Global (MJ/m^2) /yr.	Direct (MJ/m^2)/ yr.	Diffuse (MJ/m^2)/yr.	Temperature (°C)	Rainfall (mm)
Winter	1.15	0.76	0.60	17	98.2
Summer	1.89	0.86	0.87	30	41.4
Monsoon	1.43	0.54	0.89	31	683.4
Post-Monsoon	1.17	0.68	0.64	26	99.8
Annual	1.41	0.72	0.75	26	922.8

Table 2. The maximum and minimum temperature over Varanasi from 2010-2014

Sr. N.	Year	Temperature (°C) (annual average)		Temperature in summer season (°C)	
		MAX	MIN	MAX	MIN
1	2010	32.70	21	45	21
2	2011	31.46	20	45	16
3	2012	31.34	21	46	19
4	2013	31.16	20	45	18
5	2014	32.61	20	47	18


DIRECT
1.50
1.00
0.50
0.00
MJ/m²
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
Time intervals (Hours)
2010
2011
2012
2013
2014
AVERAGE
DIFFUSE
2.00
1.50
1.00
0.50
0.00
MJ/m²
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
Time intervals (Hours)
2010
2011
2012
2013
2014
AVERAGE
GLOBAL
2.50
2.00
1.50
1.00
0.50
0.00
MJ/m²
8:00
9:00
10:00
11:00
12:00
13:00
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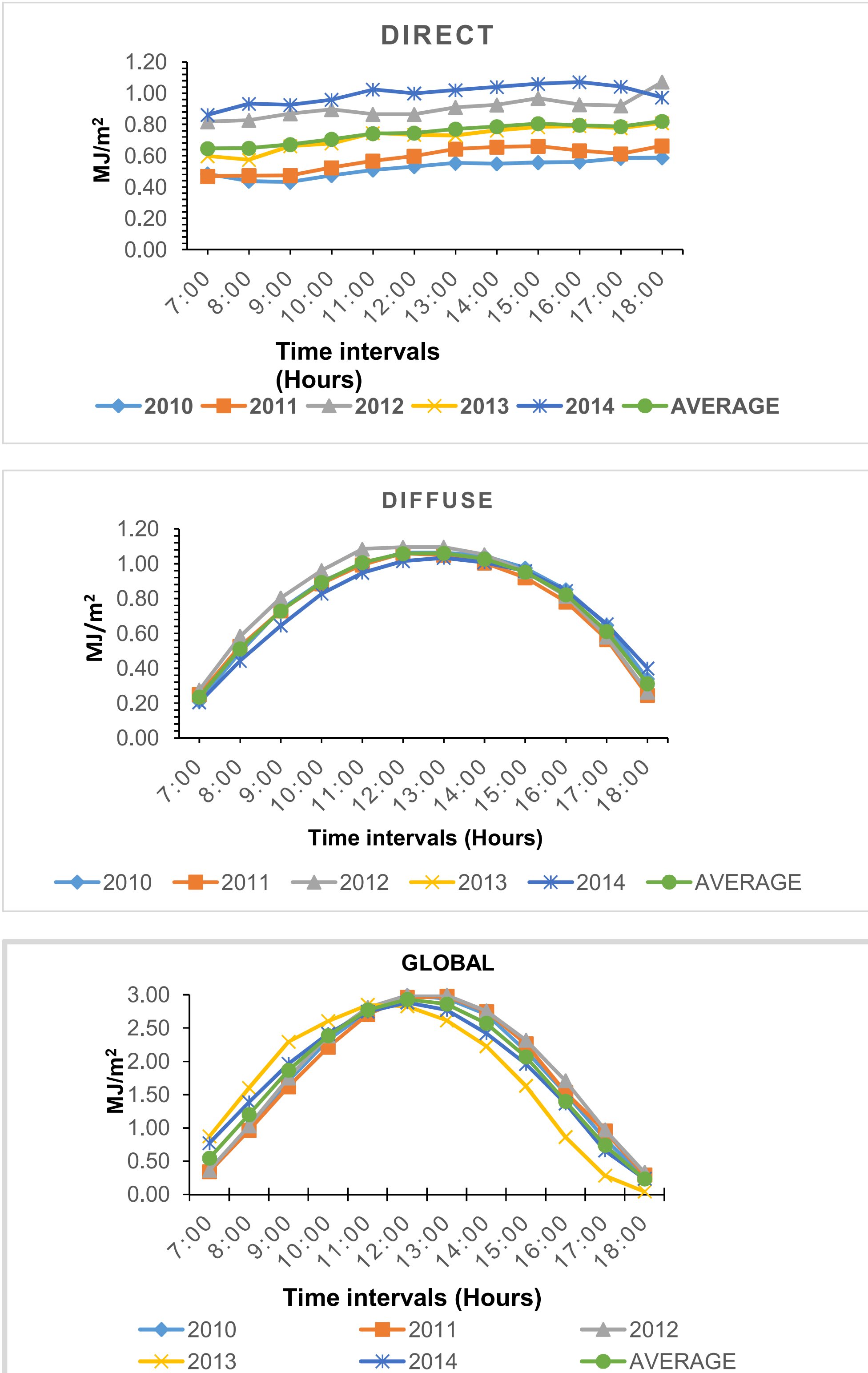
Time intervals (Hours)
2010
2011
2012
2013
2014
AVERAGE

(a)


DIRECT
MJ/m²
1.20
1.00
0.80
0.60
0.40
0.20
0.00
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00
Time intervals (Hours)
2010 2011 2012 2013 2014 AVERAGE
DIFFUSE
MJ/m²
1.20
1.00
0.80
0.60
0.40
0.20
0.00
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00
Time intervals (Hours)
2010 2011 2012 2013 2014 AVERAGE
GLOBAL
MJ/m²
3.00
2.50
2.00
1.50
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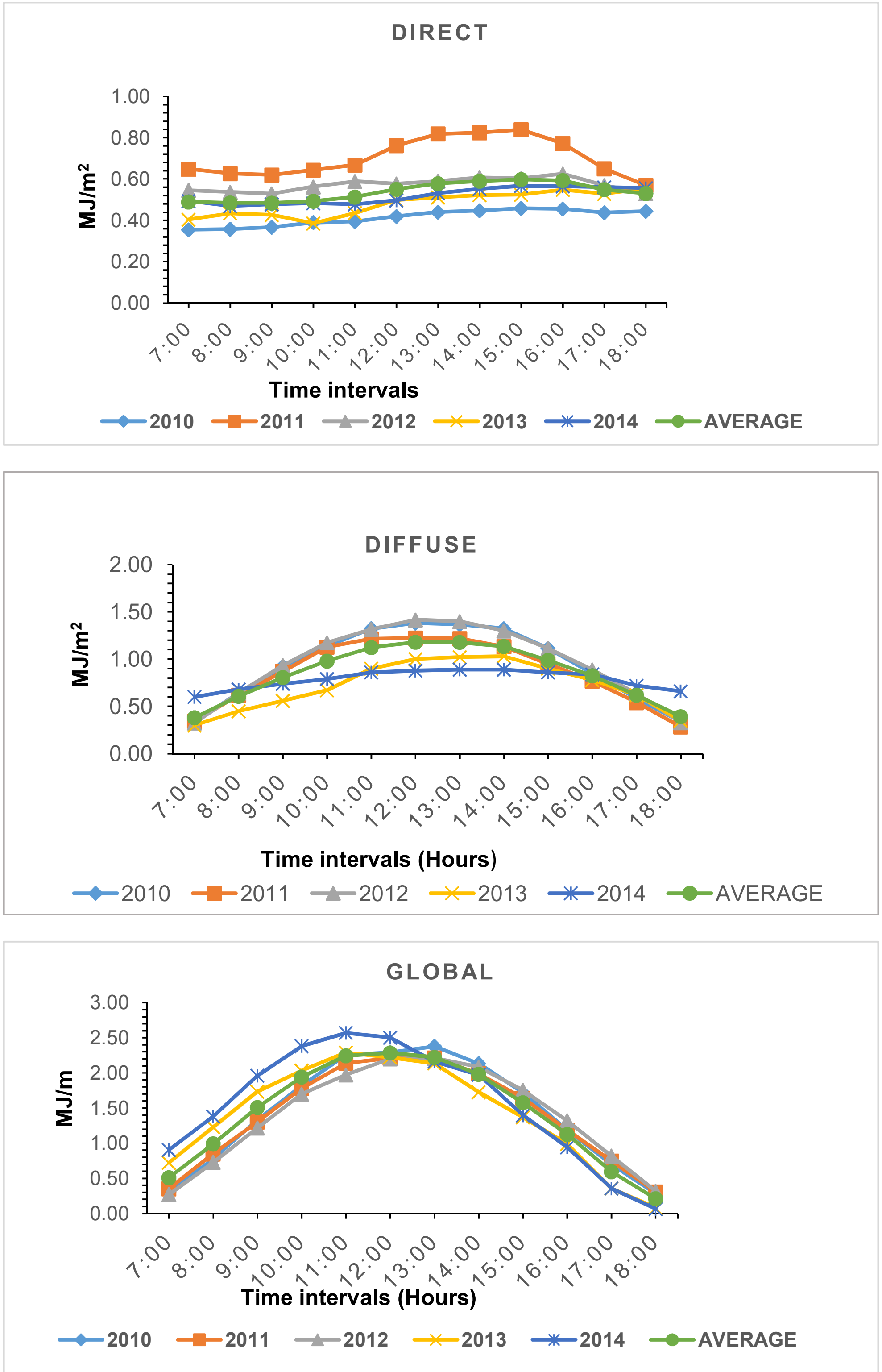
Time intervals (Hours)
2010 2011 2012
2013 2014 AVERAGE

(b)


DIRECT
1.00
0.80
0.60
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0.00
MJ/m²
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12:00
13:00
14:00
15:00
16:00
17:00
18:00
Time intervals
2010
2011
2012
2013
2014
AVERAGE
DIFFUSE
2.00
1.50
1.00
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MJ/m²
7:00
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14:00
15:00
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18:00
Time intervals (Hours)
2010
2011
2012
2013
2014
AVERAGE
GLOBAL
3.00
2.50
2.00
1.50
1.00
0.50
0.00
MJ/m
7:00
8:00
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10:00
11:00
12:00
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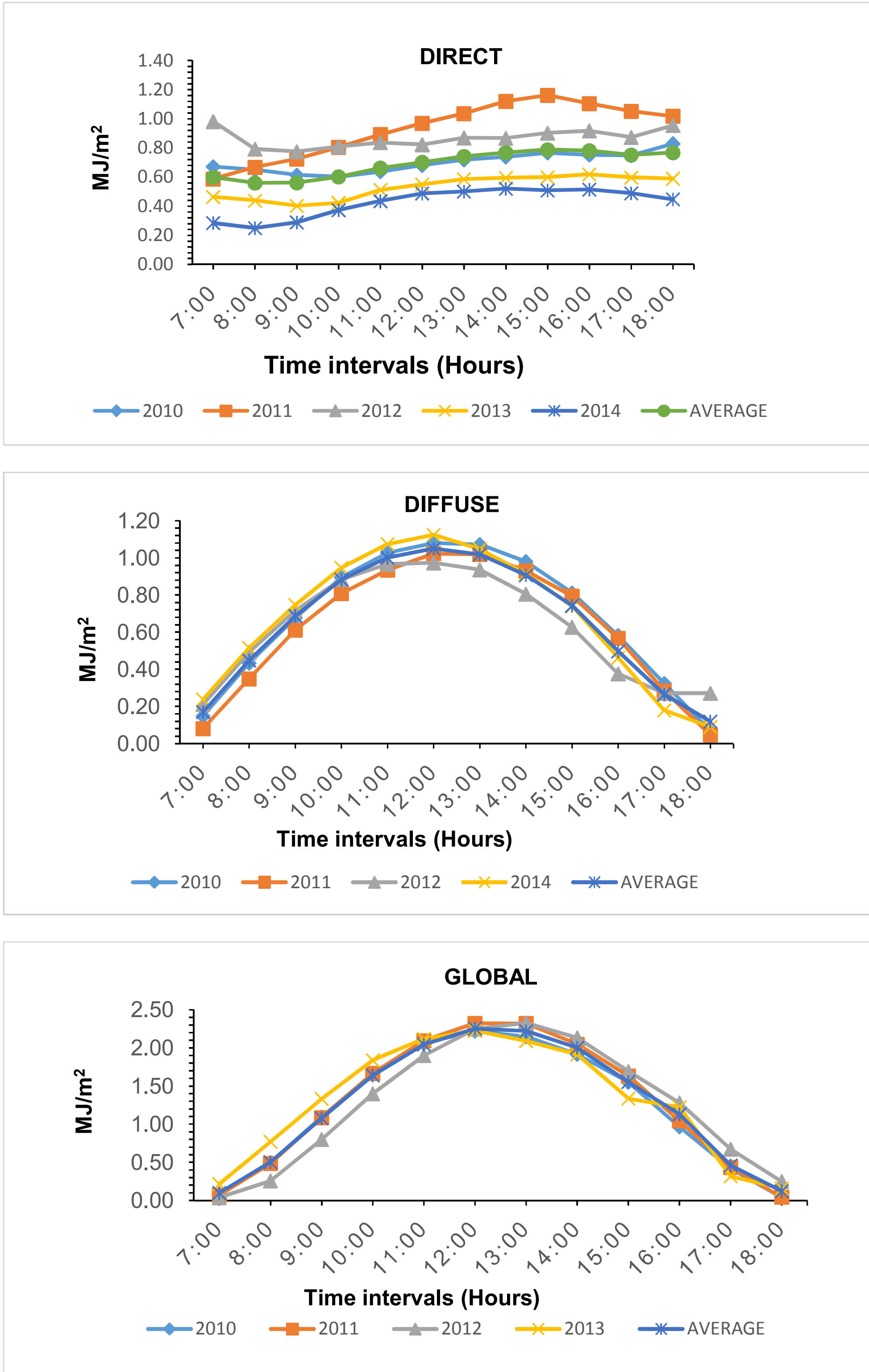
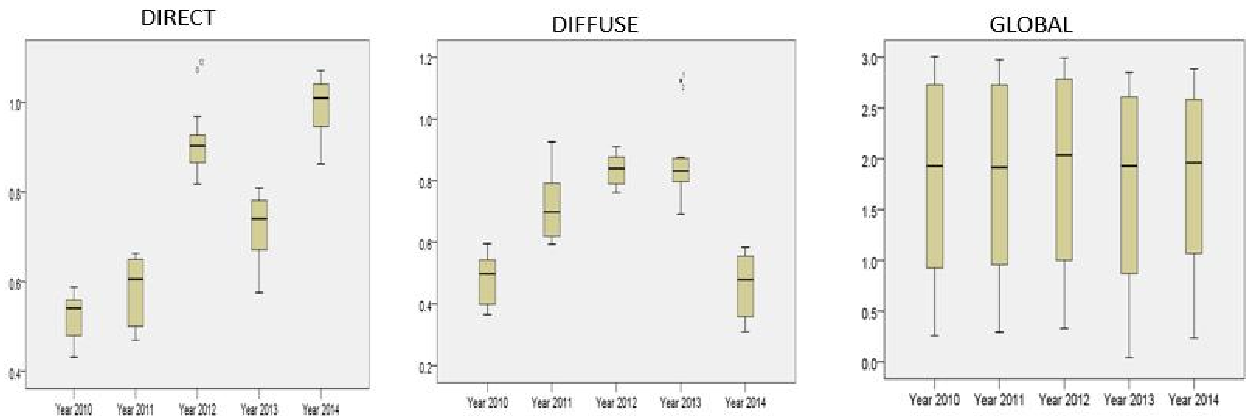
17:00
18:00
Time intervals (Hours)
2010
2011
2012
2013
2014
AVERAGE

(c)

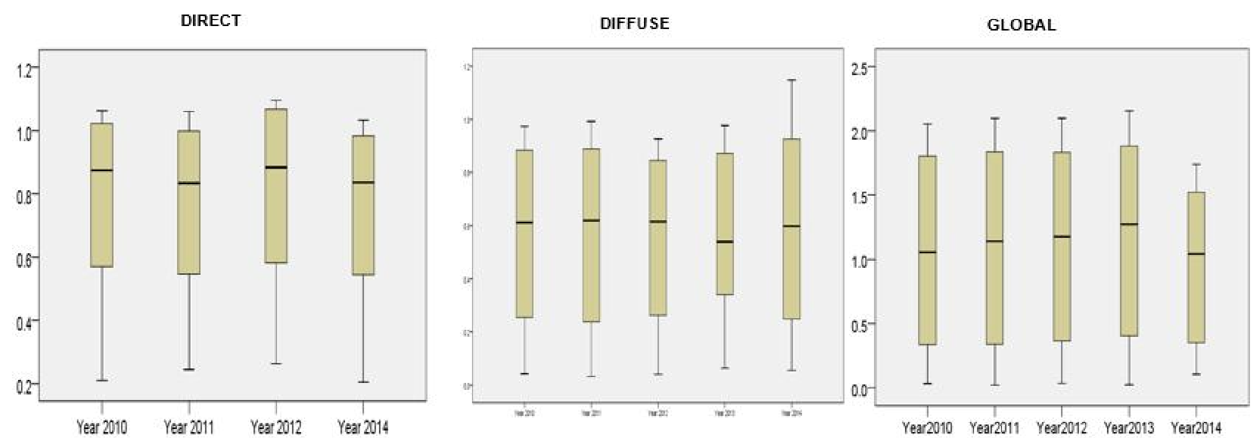


(d)

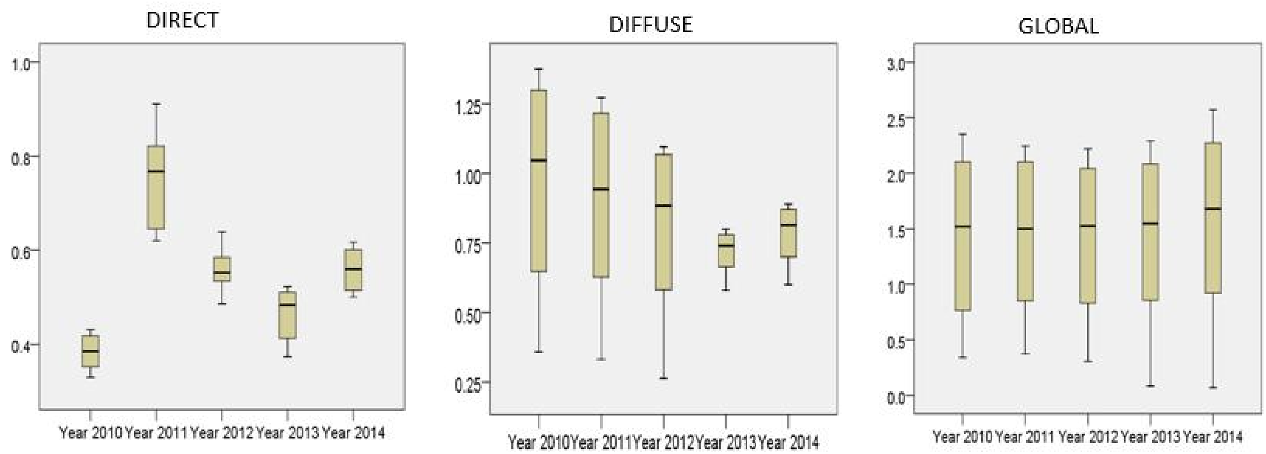
Fig. 1 (a-d). Yearly variation of solar radiation for winter, summer, monsoon and post monsoon season, respectively


DIRECT
DIFFUSE
GLOBAL
Year 2010
Year 2011
Year 2012
Year 2013
Year 2014

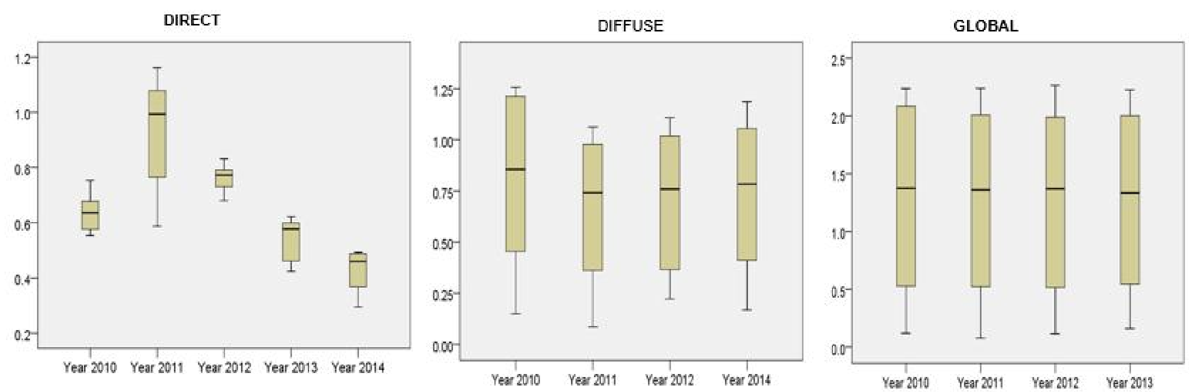
(a)


DIRECT
DIFFUSE
GLOBAL
Year 2010
Year 2011
Year 2012
Year 2014
Year2010
Year2011
Year2012
Year2013
Year2014

(b)

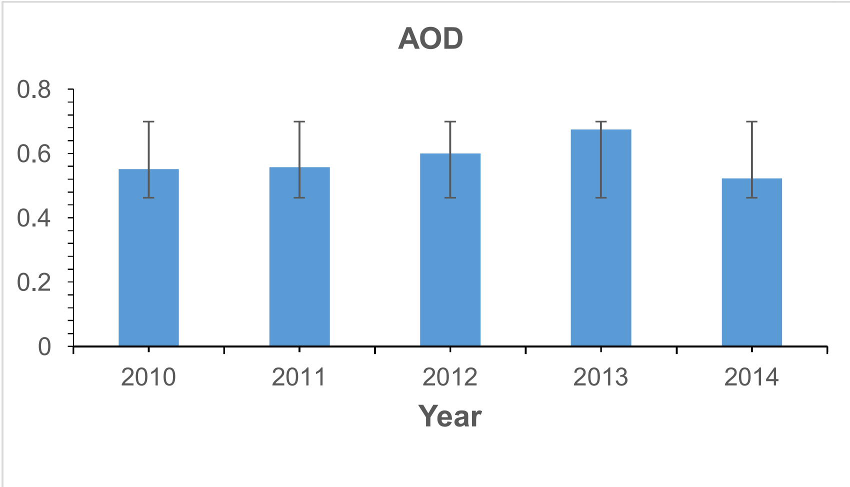


(c)



(d)

Fig. 2 (a-d). Open- high- low plot for winter, summer, monsoon and post monsoon seasonrespectively (Note: Y axis represent the solar radiation MJ/m²)



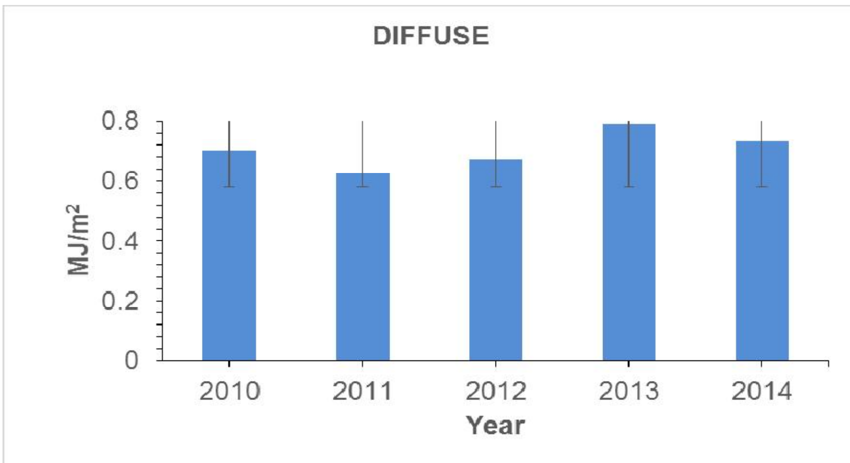
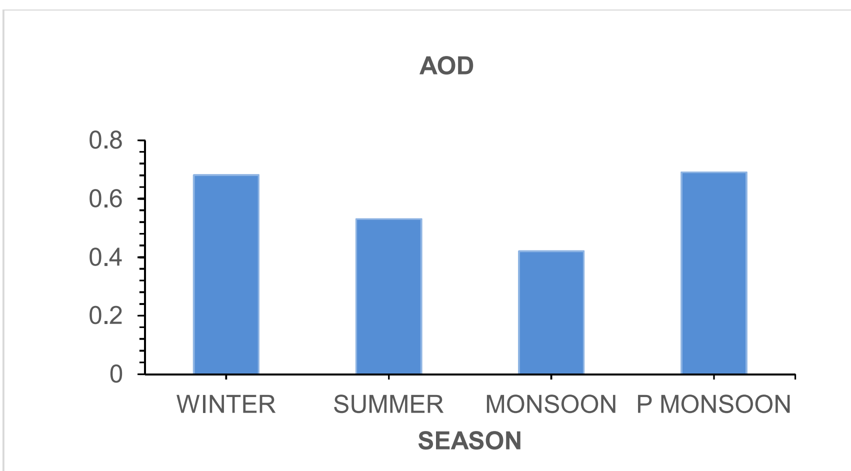


Fig. 3. Annual variation of AOD and Diffuse radiation



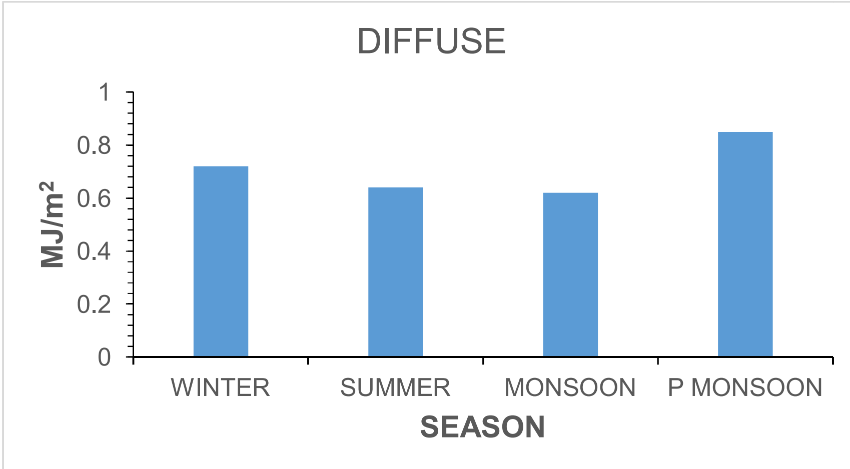


Fig. 4. Seasonal variation of AOD and diffuse radiation

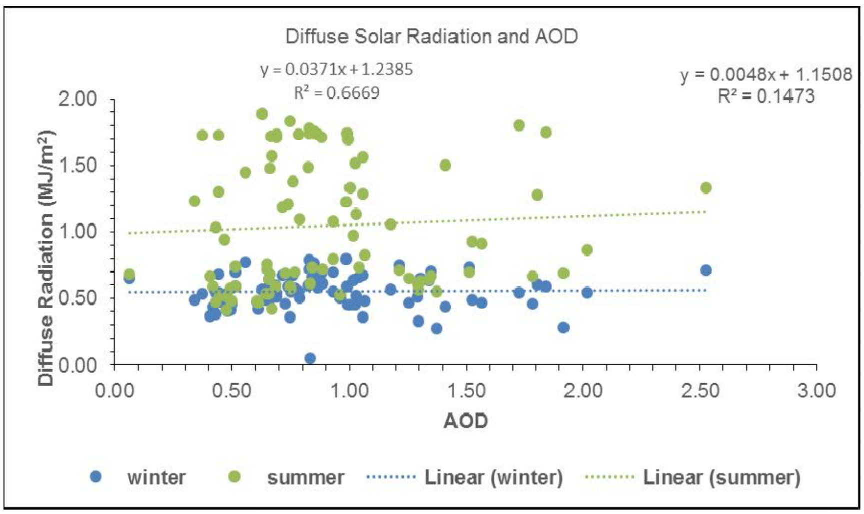


Fig. 5. Interrelation between diffuse solar radiation and AOD (550 nm)

5. CONCLUSION

The direct, global and diffuse radiation incident on the surface has been analyzed over Varanasi for five year period (2010-2014). The solar radiation depends upon the topography as well as local weather condition that control the available solar radiation.

The results obtained in the study showed an increasing trend in diffuse solar radiation pattern for Varanasi. The decrease in sunshine duration was concomitant with the decrease in global solar irradiance. It is concluded that the solar radiation varies with season. The total solar radiation was higher in the summer season than in winter, monsoon and post monsoon. The annual average of diffuse solar radiation observed over Varanasi for the period 2010-2014 is found to be 0.75 MJ/m² per year while during winter, summer, monsoon and post-monsoon seasons it is 0.60, 0.87, 0.89 and 0.64 MJ/m^2 per year, respectively.

The surface T_{max} during summer season shows an increasing trend while a declining trend in the annual average temperature over Varanasi is recorded. It might be due to AOD that play a major role in reducing the solar radiation reaching the surface. Higher AOD values as well as changes in cloud properties contribute to this difference. However, long term data analyses are required for understanding decadal changes and policy implications for the region.

ACKNOWLEDGEMENTS

The authors wish to express sincere thanks to Indian Meteorological Department Ozone Unit, Varanasi and ISRO-ARFI for provision of required data. ISRO-ARFI is also acknowledged for provision of data. We also acknowledge Giovanni online data system, developed and maintained by the NASA GES DISC.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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