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Inter-Annual and Seasonal Variability in Ambient Ultraviolet-B Radiation Level at a Tropical Region of Indo-Gangetic Plain

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Abstract: **This study evaluated the annual, seasonal, and diurnal variations in the ambient UV-B levels at a tropical region of the Indo-Gangetic plain during 2016 – 2018. Prominent seasonal variations in ambient Ultraviolet-B (UV-B) levels were recorded. Daytime cumulative UV-B varied from 16.75-37.45 (2016), 13.08-35.89 (2017) and 14.76-34.5 (2018) during summer; from 24.02-3.65 (2016), 18.32-3.11 (2017) and 11.09-2.09 (2018) during winter and 25.56 – 41.17 (2016), 20.1 – 39.21 (2017) and 14.82 – 37.18 (2018) during rainy season. The ambient UV-B level was dependent on numerous meteorological variables (cloud cover, relative humidity, rainfall, and sunshine hours), astronomical factors (Solar Zenith Angle), and pollutants (like tropospheric ozone, sulphur dioxide, nitrogen dioxide, and aerosols). Monthly average UV-B levels positively varied with sunshine hours and PAR and inversely varied with cloud cover. This study suggests that the region is exposed to highly dynamic UV-B levels, which could be a potent threat to plants specially grown during summer-rainy seasons. The study could be further expanded for the entire region using various mathematical tools.**

Index Terms: **Aerosol, Ambient UV-B, Astronomical, Clouds, Gaseous pollutants, Meteorological**

I. Introduction

Earth receives both light and energy from the sun; however, the entire light fraction is not useful for plants and animals. The solar light coming from the sun includes the shorter wavelength UV radiation (200-400 nm), PAR (400-800), and infra-red radiation. Ultraviolet is one of the minor components of non-ionizing solar radiation, which is further divided as UV-C (200-280 nm), UV-B (280-315 nm), and UV-A (320-400 nm). UV-B has the shortest wavelength reaching Earth's ground surface, representing up to 1.5% of extra-terrestrial irradiance. It's attenuated upto 0.5% or less of total irradiance reaching 33the Earth's surface (Blumthaler et al., 1997). It is well known that life on Earth becomes possible only after the formation of the global stratospheric ozone (O_3) layer. It protects life against harmful solar UV radiation (Kondratyev & Varotsos, 1996). The stratospheric O_3 layer was first discovered in 1913 by French physicists, Charles Fabry and Henri Buisson (Thangavel & Reddy, 2011). Stratospheric O_3 concentration is measured in the 'Dobson unit' named on G.M.B Dobson, who invented spectrophotometer (Anderson et al., 2012).

In an unpolluted atmosphere, the formation and degradation rate of O_3 is constant; thus, the total ozone level remains the same in the stratosphere (Divya et al., 2014). Anthropogenic activities badly affect the normal atmospheric processes, resulting in more ozone molecules degradation in the stratosphere, causing an imbalance between formation and degradation is one of the major concern (Thangavel & Reddy, 2011). Anthropogenically generated chemicals such as Chlorofluorocarbons (CFCs), Hydrofluorocarbons (HCF's), and chlorine and bromine compounds are the main ozone-depleting factors, commonly known as ozone-depleting substances (ODS). It was first suggested by Molina & Rowland, (1974) in 1974, that the artificial group of the compound known as CFCs, was likely to be the main source of ozone depletion. These chemicals destroy the ozone at an alarming rate by stripping an atom from ozone molecules. These (ODS) have a long lifetime and are highly volatile, easily reaches the stratosphere (Anwar et al., 2016), react with the ozone molecules, and release the oxygen atom from O_3. The CFCs are now accepted as the main cause of ozone depletion. The other main ozone-depleting substance that was not discussed in Montreal protocol in 1987 is the N_2O, which is naturally and anthropogenically generated mainly through the use of fertilizer in the agricultural sector to increase the yield.

Due to the depletion of stratospheric ozone, the solar spectrum's harmful rays (UV-B) reach higher to the Earth's surface, especially near the equator and the high altitude geographical zone. It is an important environmental concern as these energetic rays are quite deleterious for plants and animals, and exposed materials like paints, plastic, and other matters (Andrady et al., 1998; UNEP, 1998). In humans, it can cause a number of health issues like cataracts, immune-suppression, skin cancer, and photoaging (Ichihashi et al., 2003; Norval, 2006; Perera & Cullen, 2017; Wlaschek et al., 2001). The increased surface UV-B irradiance can cause huge deleterious effects on a number of species such as nitrogen-fixing microbes in paddy fields (Hader, 1996), phytoplanktons (Cullen & Neale, 1994), food crop (Caldwell et al., 1998; Krupa & Kickert, 1989), in the forest (Laakso & Huttunen, 1998) and aquatic ecosystem (Day & Neale, 2002; Rozema et al., 2002). The UV-B radiation is absorbed by the macromolecules such as proteins, lipids, and nucleic acid, leading to negative impacts on their natural structure and functions.

During 1977 and 1985, stratospheric ozone depletion was moved from the national to the international political arena. In 1985, the Vienna Convention legitimized stratospheric ozone depletion as an international political issue and provided a Protocol framework (Morrisette, 1989). On 14-16 September 1987, a conference on United Nations Environmental Programme plenipotentiaries created the "Montreal Protocol on Substance that Depletes the Ozone layer," which was signed by 24 nations. It is an international agreement designed to mitigate the worldwide production and use of ODS. The protocol was developed by negotiation between UNEP and major CFCs producing countries. The aim of this protocol was to aware the world about the depletion of stratospheric ozone by CFCs, which demands its protection. It is the first international treaty for mitigating a global atmospheric problem. The Montreal Protocol came into force as scheduled on January 1, 1989 (Morrisette, 1989). Nitrous oxide (N_2O) is the largest remaining anthropogenic threat to the stratospheric ozone layer not regulated in Montreal Protocol, but it is controlled under the 1997 Kyoto Protocol as a potent greenhouse gas (Kanter et al., 2013).

The UV-B intensity on Earth surface showed variation; it is modified by a number of factors like total ozone column (TOC), solar zenith angle (SZA), Earth’s sun distance, altitude above the sea level, cloud coverage (depend on the type of clouds), aerosol, tropospheric gaseous pollutants (SO_2, NO_2, and O_3), the season of the year and time of the day (Raman et al., 1996). The Cumulus-type clouds were found to attenuate up to 99% of the incoming UV-B radiation during overcast conditions (Raman et al., 1996). The concentration of dust particles, aerosol, and gaseous pollutants (SO_2, NO_2, and O_3) varies, depending upon the location. It has been observed that polluted locations show a large reduction in surface UV irradiance compared to pristine locations due to aerosol in the boundary layer (Kazadzis et al., 2007). The stratospheric ozone concentration in tropical latitudes is related to a balance between formation and destruction (Stick et al., 2006).

Keeping in view the adverse effects of UV-B on plants and human health at different geographical locations, with more influence at the equatorial and tropical region, with lack of UV-B monitoring data, especially from these regions led to conduct a study with an objective of long-term ambient UV-B monitoring. The monitoring site is based at Indo-Gangetic Plain, experiencing a tropical monsoon climate. Annual, seasonal, and diurnal variations in UV-B concentrations were monitored from January 2016 to December 2018. Different meteorological variables were correlated with the ambient UV-B variation.

II. STUDY AREA

The study site was situated at the Botanical Garden, Banaras Hindu University, Varanasi, India. Varanasi is situated in the eastern Gangetic alluvial plains on the bank of river Ganga at 25° 78' N latitude, and 83°1'E longitude at an elevation of 76.19 m above mean sea level. The weather in Varanasi is characterized by a dry tropical monsoon climate with three distinct seasons: summer (March-June), the rainy season (July-August), and winter (November-February). The summer season is dry, associated with strong hot winds, high temperatures during the day, and infrequent pre-monsoon rains during the late summer. During the study period from January 2016 to December 2018, the mean monthly maximum temperature during the summer season varied from 39.8 to 40.2 °C, and the mean minimum was between 26.8 to 28.2 °C.

The rainy season starts with heavy monsoons' onset towards the end of June and continues to mid-October, with 90% of the annual rainfall falling within four months. During this season, the mean monthly maximum temperature varied from 33.8 to 37.4 °C and the mean minimum from 27.33 to 29.5 °C. During winter, the mean monthly maximum temperature ranged from 27.39 to 28.83 °C, and the mean monthly minimum temperature ranged from 15.6 to 18.01 °C. Occasional light rains result from the retreating western monsoon. Table 1 shows the meteorological condition during the study period.

III. METHODOLOGY

Ambient ultraviolet irradiance and photosynthetically active radiation (PAR) was monitored eight hours per day throughout the growth period from 8:00 to 17:00 h using PMA2100, readout, and logging device (100 East Glenside Avenue, Glenside, PA) at the experimental site. The sensors of UV-B

(PMA-2106; 280–320 nm) and PAR (PMA-2132) were calibrated by the National Institute of Standards and Technology (NIST), USA (Fig.1).

Table I. Meteorological parameters recorded in different seasons during the study period (2016-2018) (s-summer, R-rainfall; W-winter)

Parameters	2016-2017			2017-2018			2018		
	S	R	W	S	R	W	S	R	W
Total rainfall (mm)	46.6	414	11.4	22.9	513	47.7	39.2	354	1.86
Mean maximum temperature (°C)	39.8	37.4	28.3	40.2	33.8	27.3	39.9	34.2	28.8
Mean minimum temperature (°C)	28.19	29.51	16.4	26.82	27.3	15.7	28	27.5	18.0
Relative Humidity (%)	27.31	52.31	45.91	26.9	70.0	10.18	28.26	67.07	6.15
Mean monthly sunshine(h)	09	09 ½	08	09	09 ½	08	09	09 ½	08
Mean cloud cover (%)	13.95	34.64	8.82	9.85	43.34	6.43	10.41	28.26	43.45

Fig.1. PMA 2100 (SOLAR LIGHT, 100 East Glenside Avenue, Glenside, USA) with two sensors

IV. RESULTS

Ambient UV-B was monitored continuously for three consecutive years, i.e., 2016, 2017, and 2018 (Fig.2). Banaras Hindu University, Varanasi, India, was the UV-B monitored site, which is geographically located under the sub-tropical zone. The whole year of this region is classified into three main seasons, winter, summer, and rainy. In different seasons, the solar intensity also showed higher variation during the rainy and summer season and least in the winter season. The three-year study observed that the highest annual mean of ambient UV-B was recorded in 2016 (22.51 kJ m^{-2} d^{-1}), followed by 2017 (22.12 kJ m^{-2} d^{-1}) and 2018 (20.04 kJ m^{-2} d^{-1}) (Fig. 2). Maximum UV-B intensity was recorded in July and least in December during the studied period.

In the year 2016, the mean value of the rainy season has the highest ambient solar UV-B (28.45 kJ $m^{-2}d^{-1}$), followed by the summer season (26.69 kJ m^{-2} d^{-1}), and winter has the least value (12.382 kJ m^{-2} d^{-1}) (Fig.3).

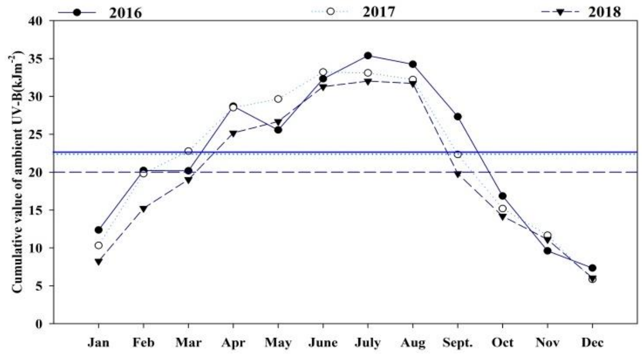

Fig.2 The month wise cumulative mean of ambient solar UV-B radiation and annual mean during 2016-17 at the monitoring site

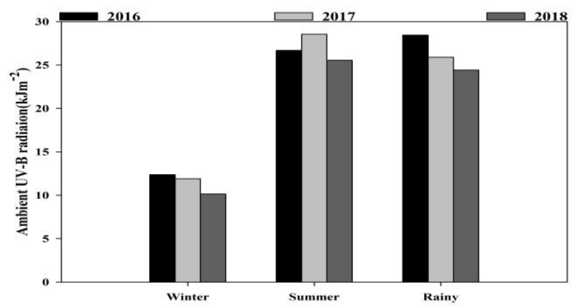

Fig.3 Seasonal variation in ambient UV-B during 2016-2018

In 2017, the highest cumulative mean ambient UV-B was recorded for summer (28.53 kJ m^{-2} d^{-1}) followed by rainy (25.90 kJ m^{-2} d^{-1}) and least in winter (11.91 kJ m^{-2} d^{-1}) (Fig. 3). Similarly, in 2018, the highest ambient UV-B was recorded during summer (25.54 kJ m^{-2} d^{-1}) followed by rainy (24.43 kJ m^{-2} d^{-1}) and least in winter (9.79 kJ m^{-2} d^{-1}) (Fig. 3). In 2016, the rainy season experienced maximum ambient UV-B, while in 2017 and 2018; maximum UV-B was received in summer, respectively. In 2018, low UV-B was obtained in all three seasons (summer, rainy, and winter) than the previous years.

During 2016, the maximum cumulative mean of solar UV-B radiation was observed in July (35.38 kJ m^{-2} d^{-1}) and lowest in December (7.34 kJ m^{-2} d^{-1}). Similarly, in 2017 the highest monthly mean was recorded in June (33.2 kJ m^{-2} d^{-1}) and lowest in December (5.84 kJ m^{-2} d^{-1}). And in 2018, the maximum UV-B mean was recorded in July (32.01 kJ m^{-2} d^{-1}) and the lowest recorded in December (6.03 kJ m^{-2} d^{-1}) (Fig. 2).

The single highest ambient UV-B irradiance was recorded on 01 July (41.16 kJ m^{-2} d^{-1}), having SZA of 3.07 °, and lowest on 26 December (3.65 kJ m^{-2} d^{-1}) having SZA of 48.12 ° at noon. In the year 2017, the single-day highest value was recorded on 9 July (39.21 kJ m^{-2} d^{-1}), having the zenith angle of 2.42° and minimum recorded on 20 December (3.10 kJ m^{-2} d^{-1}), and the zenith angle was 48.6°. The highest single-day cumulative UV-B of 2018 was recorded on 28 August (37.18 kJ m^{-2} d^{-1}) and the minimum on 20 December (2.09 kJ m^{-2} d^{-1}). The SZA at noon on

28 August and December 20, 2018, was 17.14 and 49.8°, respectively (Fig. 4).

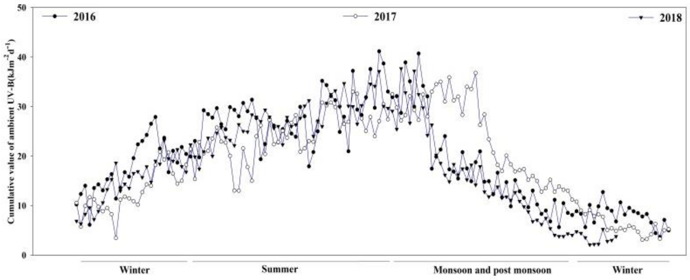

Fig.4 Ambient UV-B radiation profile of Varanasi region for the years 2016 – 2018

The solar UV-B intensity also showed diurnal variability (Fig.5). Based on our observation, the solar peak shifts in a different season; in winter (October- February), the maximum peak falls between 10.30 - 13.00, whereas from March to September, it shows maximum solar UV-B radiation peak between 10.30 - 14.00 (Fig.5). The ambient solar PAR peak showed parallel relation with the UV-B radiation (Fig.6).

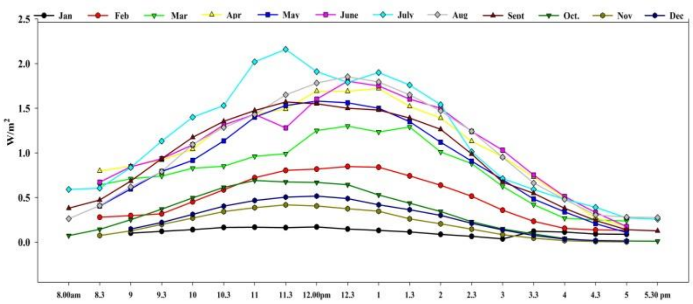

Fig.5 Diurnal pattern of ambient UV-B radiation at the study site

Diurnal variation revealed a peak in ambient level UV-B at noontime, but the peak was sharper during summer than during winter. Regression correlation analysis revealed a positive linear relationship between ambient UV-B and PAR and a cubic relationship between ambient UV-B and cloud cover. The ambient UV-B is more smooth curved during the summer but is uneven during the rainy season (Fig. 6).

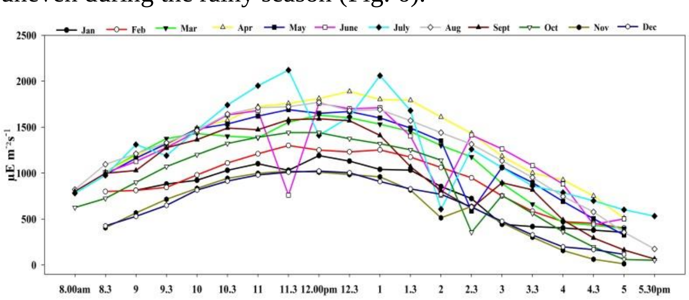

Fig.6 Diurnal ambient solar photosynthetically active radiation (PAR) of Varanasi region.

V. Discussion

In the present study, the ambient solar UV-B intensity varied year-wise, and in the year 2016, the annual mean of solar UV-B irradiance was higher compared with later studied years (2017 and 2018), which might be correlated with the less annual mean cloud coverage. The attenuation of UV-B radiation by clouds is frequently larger than any other atmospheric factors observed in 2017 compared to 2016 (Alados-Arboledas et al., 2003). The effect of cloud on UV level can vary from small enhancement to almost reduction (Matthijsen et al., 2000). The clouds attenuate the transmission of solar radiation by 10-90%, depending on the type of clouds (Palancar & Toselli, 2004). Cloud type affects the amount of ground incident irradiant flux, like Fractus cloud afforded the least UV-B transmission (0.16) while Cirrus filaments afforded the high transmission (0.97) (Norris, 2001). Whereas cumulus cloud can cause notable enhancement of solar radiation up to 34% at noontime compared with clear sky value because of the broken cloud effect observed in 2016 (Palancar & Toselli, 2004). The broken cloud is often brighter than the blue sky (Nack & Green, 1974). Low precipitation in 2018, caused poor washout of atmospheric aerosols, which scatters and absorbs the solar radiation, eventually more cloud cover. Seasonal ambient UV-B variation in 2018 also showed lower values compared to 2016 and 2017 data. Aerosol also shows yearly and seasonal variation, which depends on atmospheric, metrological conditions, anthropogenic and natural emissions sources.

The gaseous pollutant, tropospheric ozone (O_3) concentration was high during 2018, followed by 2017, and lowest in 2016 (Dolker et al., 2020). Increased tropospheric ozone strongly reduces the UV radiation reaching the ground (Acosta & Evans, 2000).

Comparing the seasonal variation of ambient UV-B during the studied years, it was observed that in the year 2016, solar UV-B influx was higher in the rainy season followed by summer and least in winter, while in the years 2017 and 2018, the highest influx was observed during summer followed by rainy and winter. The higher intensity in the rainy season of 2016 might be the cumulative effects of more sunshine hours (9 ½ hrs), rainfall, low tropospheric ozone (O_3), and aerosols. This might be correlated with aerosol washout due to monsoon rain, less relative humidity, and moderate cloud cover. Due to high precipitation during the rainy season, there is a washout of aerosol and other gaseous pollutants (SO_2, tropospheric O_3, and NO_2) from the atmosphere. The ambient UV-B radiation that otherwise could be absorbed or diffused by the aerosol particles, dust, and other pollutants in the atmosphere would have reduced irradiance on the ground surface. According to Hyvärinen et al., (2011), the average monsoon aerosol concentration decreased by 50-70% compared with pre-monsoon/summer season. The intensity of solar UV-B irradiance on the ground surface was controlled by a number of factors such as astronomical factor, total ozone column, cloud, aerosol, and varieties of regional factors such as albedo and air pollutants (O_3, NO_2, and SO_2) which are potent absorbers of UV radiation (Madronich, 1993; Repapis et al., 1998; Zerefos et al., 1995), therefore it was observed that air polluted days have less solar UV-B irradiance

(36.4%) than an unpolluted day. The IGP is characterized by significant sulphate aerosol loading, which forms the major constituent comprising about 29% of total aerosol (Sharma et al., 2003; Satheesh & Ramanathan, 2000). Li et al., (2017) reported a 50 % rise in SO_2 emission in India during the years 2004-2016. According to Zerefos et al., (1986) the air pollutant SO_2 is one of the powerful UV-B absorbers, having the capacity to reduce 2.5% ambient UV-B at surface level in the urban region by rising only 1%. Other pollutants emitted from different sources (natural and anthropogenic), e.g., forest fires in Himalayan foothills (Vadrevu et al., 2013), the residue of agricultural crop burning (Kumar et al., 2011), urban development and industrial fossil fuel combustion, from transport vehicle sources, and dust with aeolian origin (Palancar & Toselli, 2002; Ram et al., 2012). The IGP region is one of the world's densely populated areas, hosts about 40% of the total Indian population (Devi et al., 2020; Tiwari et al., 2015). Aerosol over the IGP region exhibits a pronounced seasonal and inter-annual variability (Kaskaoutis et al., 2011), strongly depend on anthropogenic and natural aerosol emission, local and regional, metrology, and atmospheric dynamics (Nair et al., 2007).

The year 2017 and 2018 data records showed the highest UV-B intensity in the summer season, followed by rainy and winter. During the 2017 summer, there was lower humidity and lesser cloud cover (%), which permits the direct and higher penetration of ambient UV-B at the ground surface compared to the 2016 summer. While in the rainy seasons of 2017 and 2018, higher relative humidity and cloud cover have played a role in reducing UV-B radiation compared to the summer level. The tropospheric ozone of the studied site showed good relation with the year-wise annual solar ambient UV-B. With the increased concentration of tropospheric O_3 level, the ambient solar intensity and ambient UV-B decreased. Here tropospheric O_3 played an excellent role in the attenuation of harmful solar UV-B.

And during the winter season, the lowest ambient UV-B was recorded in 2016, 2017, and 2018 and a similar outcome has been reported earlier by Beckmann et al., (2014), who reported that during winter in the northern and southern hemisphere (January/ July), UV-B irradiance was lowest in the mid-latitude and decline to zero beyond the polar circles, where solar insolation is absent during polar night. During the winter season, the IGP belt is under the influence of frequently foggy and hazy conditions that affect solar radiation's reach at the surface level (Gautam et al., 2007). In winter, at the IGP region, the pollutant level increases (Kaskaoutis et al., 2011; Lu et al., 2011). High aerosol during winter was found because of the deficit of rainy washout, increasing emission from anthropogenic sources either from industrial, coal thermal plants, biomass and biofuel burning, automobile exhausts (Kaul et al., 2011). The anthropogenic aerosol is highly hygroscopic and serves as condensation nuclei to form fog and hazy conditions during winter. High aerosols, foggy and hazy conditions, gaseous pollutants (i.e., SO_2, NO_2, and O_3), along with astronomical factors (solar elevation), limits the UV-B influx at the surface level. The gaseous pollutants and water vapor produce a remarkable attenuation by scattering and absorption of solar irradiance that reaches the Earth's surface (Lorente, Redano A, X.De Carbo, 1993). During the winter season, the tropospheric O_3 level at the same site was higher compared to the rainy season during 2016-2018 (Dolker et al., 2020). Increased tropospheric ozone strongly reduced the UV radiation at the ground level (Acosta & Evans, 2000). An increase in solar zenith angle and pollution during the winter season favors the reduction of ambient solar UV-B and PAR intensity. The attenuation of UV-B radiation is also described by the Beer-Lambert law, which states that increasing the particle density along with the elongation of path reduces the light traveling capacity, as the particles can play a role in the absorption or scattering of light.

In winter, especially high aerosol optical depth swings over the eastern IGP depending upon the weather condition, the monitoring site is based at the east IGP region (Kaskaoutis et al., 2011).

The month-wise comparison showed that the mean ambient UV-B intensity was highest in July and lowest in December. In July, the rainfall was high, and relative humidity was low compared to other monsoon months. High rain in July sweeps the atmospheric pollutants that clean the solar radiation path and favor the maximum reach of ambient UV-B on the ground surface, and sweeping of local pollutants from the atmosphere reduces air mass. The air mass content has a direct relationship with solar radiation attenuation. On the increase in air mass, the ambient UV-B influx reduces and vice versa. However, in December, low mean ambient solar UV-B radiation can be correlated with large SZA and more pollutants load in the atmosphere. Rainfall was negligible in winter, which means high aerosol content and gaseous pollutants like SO_2, NO_2, and O_3.

In a diurnal study of ambient UV-B and PAR, the maximum value of both UV-B and PAR was observed between 11.30 to 1.30 pm. as, during this time, the zenith angle reduces maximally, and path length, near the noontime, becomes the shortest, which favor the direct reach of radiation at the ground surface. Lesser the path length means lesser the attenuator content in their way, thus favors higher UV-B reach to the surface level.

VI. Conclusion

The three-year UV-B monitoring data revealed maximum UV-B during rainy (2016) and summer (2017 and 2018) seasons. The maximum level reached was 41.17, and the minimum level was 2.09 kJ m^{-2} d^{-1}. Hourly maxima were recorded near noontime, which was found to be higher during the summer rainy season and minimum during the winter season.

The ambient average UV-B declined from 2016 to 2018, with more variation during the rainy/summer season than the winter season. IGP region marks heavy aerosol loading during pre-monsoon period, which plays a significant role in attenuating the solar light. IGP supports major agricultural activities, and most of the crops in the region are grown during the summer/rainy season, and thus an alternative approach for mitigation can only be based on monitoring data. Cloud cover (%) and type also play a role in attenuating or modifying ambient UV-B levels. This monitoring data can predict the regional UV-B levels and can be used to raise various modeling tools.

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