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Research Article
Characterisation of the Broadband Solar Ultraviolet Spectral Irradiance over Bangi, Malaysia

[1]Ohoud Aljawi, [1,2]Nurul Shazana Abdul Hamid, [1]Wan Mohd Aimran Wan Mohd Kamil and [3]Nor Sakinah Mohamad

[1]School of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[2]Space Science Centre (ANGKASA), Institute of Climate Change, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[3]PERMATA Pintar National Gifted Centre, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

Abstract
Background and Objective: Stratospheric ozone depletion, high skin cancer rates and increased public benefit have strong dem and for solar ultraviolet radiation measurements. This study aimed to characterize the broadband of solar UV spectral irradiance in Bangi, Malaysia. Apart from that, it also attempt to estimate the solar UV broadband radiation intensity with a utilization of establish mathematical model. **Materials and Methods:** Observation of broadband solar ultraviolet (UV) spectral irradiance 300-400 nm over fixed time interval between January, 2014 and July, 2015 have been measured and analyzed. The experimental measurements were obtained by using a portable Avantes Avaspec ULS 2048×64-USB2 spectrometer on horizontal surface at Universiti Kebangsaan Malaysia, in Bangi (2°55' N, 101°46' E and 50 m above sea level). The direct radiation measurement technique was acquired by pointing the sensor directly to the sun. The statistical test parameters such as root mean square error RMSE and mean bias error MBE have been used to test the accuracy of measured data. **Results:** The study reported that, the maximum recorded hourly average value of ultraviolet radiation intensity was 47.37 and 46.36 Wm^{-2} in month of July during the period 2014-2015, respectively, while the minimum value recorded 36.82 Wm^{-2} in month of November, 2014. In addition, the mathematical model results are comparable with measurement data for broadband solar ultraviolet intensity. The results were compared with the regions of Penang in Malaysia and Nakhon Pathom, Thailand. **Conclusion:** It was discovered that the variation of diurnal UV radiation is almost follows the same trend for all measured value at clear days. The statistical analysis of the present result also revealed that there is strong relationship between measured and estimated UV intensity, indicating the effectiveness of the measurement values.

Key words: Avantes spectrometer, ultraviolet radiation, experimental measurement, mathematical model

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Corresponding Author: Ohoud Aljawi, School of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Evidence of ozone depletion in the stratosphere caused by several chemicals and long-term exposure of human skin to ultraviolet radiation could induce skin cancer. Furthermore, the tropical region is opulent in the solar radiation. Therefore, the dem and for data on solar ultraviolet radiation UV has increased markedly and this has led many researchers to establish their method to observed UV radiation[1–3]. The ultraviolet (UV) solar irradiance corresponds to the radiative produce from the sun in the spectral range 100-400 nm. The UV radiation arriving on the ground in form of direct radiation, diffuse radiation and global radiation which consists of direct and diffuse beam. Moreover, the direct irradiance is radiation remaining unabsorbed and unscattered photons. Direct radiation responsible for casting of shadows[4]. Solar UV irradiance is a driver of several photochemical reaction and it is dependable on the formation of the ionosphere and other atmospheric event[5]. It impacts in human health both positively and negatively. Apart from that, UV broadband irradiance is a limit wavelength and greater energy than visible light.

Solar (UV) broadband irradiance is transferred over the Earth's atmosphere and can be divided into three fundamental combination of arriving irradiance relying on their wavelength range; which are UV-C, UV-B and UV-A. The UV-C has spectral area of 100-280 nm. It has the huge energetic fraction of the UV spectrum, which does not extent the terrestrial level. This spectrum is completely consumed by relative optical ozone mass and other atmospheric elements[1,6,7]. On the other hand, UV-B spectral has area between 280-315 nm and greatly absorbed by stratospheric ozone, but still attains the earth level. The UV-B spectral has harmful results in many biological organizing. For instance, spectral range 280-315 nm can lead to skin sunburn, skin cancer, deactivate proteins DNA, eye cataracts in humans, casualties of productivity and other damaging effects in plants[8-10]. However, this UV-B also can be possessing advantageous. It helps to build and maintain human bones by producing vitamin D as well as it could prevent against certain kinds of cancer[11]. UV-A wavelengths (315-400 nm) is minimal active section in the UV range. It is less absorbed by ozone mass and characterize most of the UV solar radiation at the earth surface. Besides that, the UV-A radiation is the major portion about 90% of the overall UV solar radiation lower than 400 nm reported by Koronakis *et al.*[12]. Several studies demonstrated that UV-A is also dangerous, cause skin deterioration, early skin senility and crease likewise eye illness[11]. The effects of these various UV radiation have given rise to the awareness in studying their variations in different places, especially those close to the equator region which received abundant radiation throughout the year.

In theory, the solar UV broadband irradiance scale build considerably on various atmospheric and surface parameters: The air mass traversed by the normal solar radiation, that rely on the solar zenith angle, the elevation of the experiment location, atmospheric extinction operations e.g., aerosols and trace gases and metrological status, e.g., turbidity and terrestrial albedo[13-15]. The standard solar UV broadband irradiance is the highest under clear skies, while with cloud cover, UV could be increase. The maximum elevation and a light atmosphere layer may absorbs less UV radiation[16].

The present paper is focusing on characterizing the annual variation of direct irradiance for solar ultraviolet irradiance for the hourly measurements. This type of measurement has been less studied. Most of published experimental results use measured value of global UV radiation[10,16,17]. Therefore, the direct radiation of solar ultraviolet is important in designing systems employing solar energy such as high intensity solar cells[18]. Moreover, the measurement of solar spectral irradiance is uncommon in many areas throughout the world. This principally due to the spectral irradiance measuring system are more elaborate calibration process. In addition, the type of the sensor for the instrument can be leading to increase the costs[19]. Unfortunately, the economic barrier has contributed to the lack of spectral databases. The advantage of measurement of direct solar spectral irradiance is the incoming solar radiation must first be separated by wavelength before the detector records the signal. Due to the absence of high resolution spectral measurements which are possible only with very advance instrument. A simple and inexpensive instrument can observe the direct solar ultraviolet spectral irradiance. Besides that, forecasting the UV intensity at solar noon can be obtained by using the mathematical model data. This research shows an inclusive series of mean measurement of UV broadband solar radiation in the wavelength range of 300-400 nm for direct irradiance at Bangi, Malaysia. The collected data are then compared with the measurements from other regions nearby Malaysia. This study also validating the result by comparing it with estimated data which can calculate by using mathematical model.

MATERIALS AND METHODS

Solar ultraviolet broadband irradiance has been measured using a lightweight apparatus starting January, 2014. The instrument was situated at the open area of the third floor of the School of Applied Physics building of Universiti Kebangsaan Malaysia, with coordinates of 2°55' N latitude and 101°46' E longitude and is 50 m above sea level. These data are also representative for locations surrounding Bangi, Selangor that share the same climatic regime. The data collection period was from January, 2014-June, 2015, where the daily observation started from 8:00 o'clock in the morning to 6:00 o'clock in the evening at local time. The measurements range of solar ultraviolet spectrum beginning from 300-400 nm in unit W cm^{-2} nm^{-1}. In addition, the atmospheric status at particular time was identify as thick rainfall and cloud. However, it should be noted that, the measurement of direct beam of UV irradiance was obtained by pointing the sensor to the sun. The UV data analyzed in this study is the average of the instantaneous irradiances arriving at ground level.

The spectrometer Avantes AvaSpec ULS 2048×64-USB2 was employed to record the solar ultraviolet broadband irradiance. The spectrometer resolution is 1 nm and the measurement monitored for the wavelength in the scope of 300-1100 nm in ultraviolet (UV), visible (VIS) and near infrared spectrum (NIR). This instrument scanned the solar radiation rapidly without the requirement of a moving grating. In addition, the solar radiation passed through the spectrometer that was linked to cosine corrector via the fibre optic at an angle view of 180°. The calibration device-Avalight-DH-CAL light source calibrated the spectrometer every 60 h for UV/VIS/NIR with spectral range of 205-1100 nm. Besides that, the calibration lamp Avalight-DH-CAL has Deuterium light and Halogen light source for UV/VIS/NIR 205-100 nm. Although, halogen lamp applied to visible and near infrared 400-1100 nm. A calibration to the spectrometer was made by the National Renewable Energy Laboratory (NREL), USA using a standard light[20].

However, one important thing to consider is the climate in Malaysia that is usually being hot and humid most of the times due to the fact that the country is located at equatorial region. The seasonal variation of the climate in Malaysia is divided into rainy and dry seasons. The dry season exists in the second and third quarter of the year between April-September and it has southwest monsoon. Meanwhile, the rainy season exists in the third and first quarter of the years between October-March and it has a northeast monsoon[21,22].

It was further analyzed by computing the UV radiation using a mathematical model proposed by Bouguer's, Lambert's and Beer's law[23]. This model is important to validate our measurement data. The mathematical model is used for the estimation of the UV broadband radiation intensity in sun direction 300-400 nm. It is based on correlation analysis derived usually through linear regression. This method considers that, the measured solar ultraviolet broadband radiation data can be defined as a function of some separate parameter. This model included all of the impacts of atmospheric transmittance into the parameter of air mass (m)[4,24]. Bouguer's, Lambert's and Beer's[23] have put down a law that would calculate the radiation beam directly from the ground level measurement on a clear atmospheric day. That model requires only measured sun direction of terrestrial radiation and the air mass (m) at earth surface to apply Langley method[25]. This method allowed us to estimate the ultraviolet intensity in the top of the atmosphere and in the Earth surface at ground level with ground-based instrumentation:

$$I_\lambda = I_{0\lambda} \exp(-\tau_\lambda m) \quad (1)$$

where, I_λ is the solar UV intensity at the ground level and $I_{0\lambda}$ is outside the atmosphere. The quantity m refers to the air mass number or path length. The air mass is equal to one when the sun is directly overhead. Given the time of the day and site's latitude and longitude, the air mass is easily calculated using the formula of non-refractive plane parallel atmosphere of uniform density[23,26]:

$$m = \sec\theta \quad (2)$$

where, θ is the solar zenith angle.

Furthermore, t_λ is the total atmospheric extinction. The parameter in Eq. 1 could be rewritten in a linear shape as follows:

$$\text{In}I = \text{In}I_0 - \tau_\lambda . m \quad (3)$$

Apart from that, a statistical test is adapted to evaluate the performance of mathematical expressions for the solar ultraviolet estimations values. Mean bias error (MBE) and root means square error (RMSE) were statistically applied and determined. The RMSE value is always positive and defining zero at the perfect case. The root mean square error is commonly used to measure the differences between values predicted by a model and the values observed from measuring solar ultraviolet irradiance[17,27]. The root means square error is calculated from the following equation:

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n}\frac{(x_i - x'_i)^2}{n}} \quad (4)$$

Meanwhile, the MBE supply knowledge on the performance of correlations by allowing a comparison of the actual deviation between calculated and measured values. The perfect amount of the mean bias error is zero:

$$\text{MBE} = \sum_{i=1}^{n}\frac{x_i - x'_i}{n} \quad (5)$$

$$\text{RMSE}(\%) = \frac{\text{RMSE}}{\text{X}} \times 100 \quad (6)$$

where, x_i is the estimated values for solar ultraviolet radiation, x'_i is the measured values UV radiation, X is the average of the measured values and n is the total number of observations.

RESULTS AND DISCUSSION

Ultraviolet broadband solar radiation was measured in Bangi, Malaysia from January, 2014-July, 2015. The results of monthly hourly average variation of ultraviolet broadband intensity are presented in Table 1 and 2 for the years 2014 and 2015, respectively. It can be observed that, the UV broadband intensity rise with the solar altitude and reaching a maximum value between 12:00 and 13:00 at noon time. This is the most significantly affected due to solar zenith angle and the atmospheric air mass which are the minimum at noon time. Then, the intensity reduced as the solar altitude of the sun decreases. Furthermore, the maximum values of average UV intensity are located in the second and third quarter of the year starting from April-September. The maximum reported monthly hourly average of UV irradiance was 47.37 Wm^{-2} in July, 2014. On the other hand, at this time of the day the minimum values of the monthly hourly average UV radiation occurred during the months of November, December and March in the 4th and 1st quarter of the year. The lowest value of UV attained 36.82 Wm^{-2} which occurred in November at 13:00 pm. It is attractive to observed a decline of 81% between the highest and lowest values. This enormous difference is due to the great event of cloud cover and the zenith angle is increase in November. As well as, same trend has observed again in Table 2 which presented the hourly average value of ultraviolet radiation intensity a day for the months of 2015 in Wm^{-2}. The highest average value of UV recorded in 2015 is 46.36 Wm^{-2} in July which is approximately similar to the maximum average value of UV intensity in 2014.

The analysis revealed that, the diurnal variation of UV radiation exhibits a same trend for all measured days. Figure 1a-b presented the plot UV broadband radiation intensity over time for the day of maximum values on 7th July, 2014 and 16th July, 2015, respectively. It illustrated

Table 1: Monthly hourly average solar UV intensity in Wm^{-2} for 2014 at Bangi, Malaysia

Months	8	9	10	11	12	13	14	15	16	17	18
January	4.91	7.59	21.70	31.49	38.61	40.44	37.56	36.83	32.57	24.23	7.99
February	3.66	9.20	19.71	31.42	37.03	40.06	38.71	32.38	25.32	14.84	5.37
March	4.53	7.49	17.23	28.22	36.52	41.80	39.96	37.96	31.00	20.55	8.83
April	9.16	17.12	20.88	34.00	40.81	43.25	40.58	38.76	33.46	19.36	8.82
May	9.94	22.30	28.20	36.49	42.09	42.86	42.60	38.64	32.46	24.88	12.49
June	10.61	18.91	27.56	35.39	40.97	44.03	43.37	40.33	33.67	26.21	10.70
July	10.54	19.97	32.71	39.65	43.61	47.37	43.53	40.10	34.44	28.29	10.12
August	9.17	19.68	25.89	36.94	41.14	42.52	39.57	36.83	30.21	25.20	8.64
September	8.53	18.28	26.79	35.16	39.55	42.92	38.92	33.31	25.98	19.81	8.72
October	5.54	11.56	22.63	31.48	38.93	41.22	36.56	30.64	21.55	14.48	7.35
November	5.47	16.09	22.72	28.74	34.01	36.82	30.06	26.30	18.14	14.95	7.11
December	6.91	15.69	22.33	30.75	35.33	40.35	36.07	29.18	23.96	16.12	6.40

Table 2: Monthly hourly average solar UV intensity in Wm^{-2} for 2015 at Bangi, Malaysia

Month	8	9	10	11	12	13	14	15	16	17	18
January	3.54	16.24	23.58	31.87	37.81	41.63	35.99	33.33	25.51	17.19	6.48
February	6.58	13.45	26.90	37.55	40.53	40.34	39.25	32.17	24.09	16.59	7.45
March	3.23	11.74	23.88	36.69	38.06	39.70	38.47	32.67	25.67	15.46	6.00
April	6.81	17.18	25.63	35.50	40.72	43.15	39.84	37.56	31.80	17.87	10.99
May	7.12	16.02	27.91	36.28	42.19	41.59	36.40	34.77	27.22	24.01	12.57
June	10.83	19.33	23.61	33.43	36.95	43.03	44.77	39.14	33.55	22.82	13.45
July	11.76	25.84	35.63	40.34	43.33	46.36	44.49	39.71	34.31	23.24	13.33

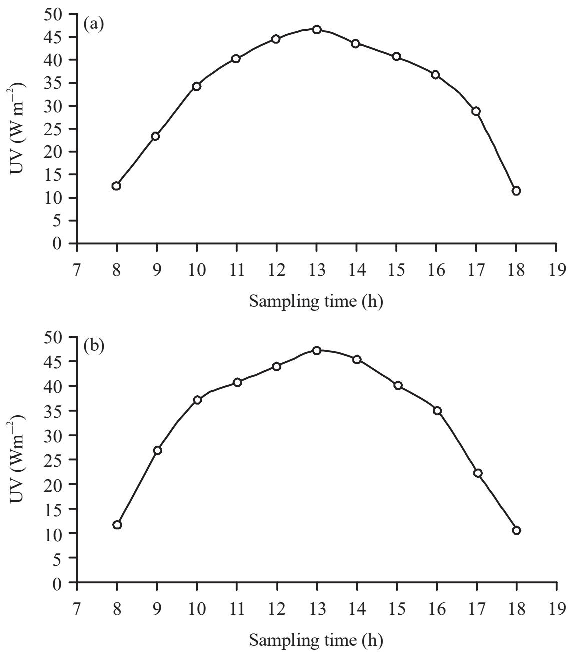

Fig. 1(a-b): Diurnal variation of UV broadband radiation intensity Wm^{-2} for (a) 7th July, 2014 and (b) 16th July, 2015

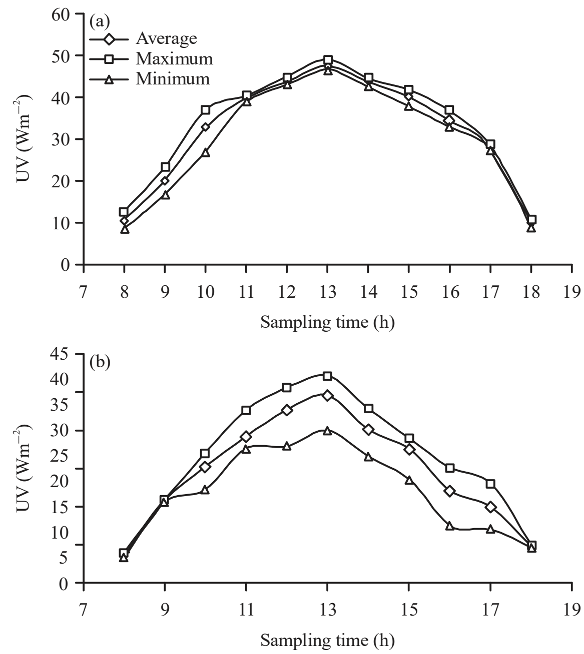

Fig. 2(a-b): Hourly maximum, average and minimum UV broadband radiation intensity Wm^{-2} in (a) July, 2014 and (b) November, 2014

that the UV radiation increases with the solar altitude and reaches its maximum value about 13:00 pm at noon time, then decreases as the solar altitude decreases. The data are sharply peaked around the middle of the day due to the existence of a clear atmosphere which results in an increase in the maximum value of the UV radiation. Figure 2a-b presented a typical dry season (July) for the maximum value and rainy season (November) for the minimum, respectively, in the variation of hourly maximum, average and minimum UV broadband radiation intensity value for 2014. As can be deduced from Fig. 2a-b, attributed to different atmospheric condition, also to zenith angle factor between to season as the sun move faster in the 4th quarter affect the amount of UV radiation reaching the earth surface.

In a comparison of UV radiation intensity in Bangi with other cities Penang, Malaysia[8], 5.34°N, 100.30°E, Nakhon Pathom, Thailand[28] 13.82°N, 100.04°E, Granada in Spain[29] 37.18°N, 3.58°W and Bahrain[7] 26°N, 50°E. Our results agreed with previous studies in Granada and Bahrain, which also having the highest rates of average hourly UV radiation in the month of July. Nevertheless, our site is located in the tropics and thus our value of UV broadband intensity is slightly higher than in Granada and Bahrain. The highest rate was character to clean sky over that month. On the other hand, studies using Nakhon Pathom and Penang data revealed that these states exhibit the highest values of UV in the April month. However, the lower monthly average rate per hour for Bangi in November, is approximately similar to the minimum value obtained in Penang, Malaysia.

Next, continue with the validation of measurement data. Regression analysis is employed to estimate the UV solar radiation intensity by using the Langley plot. Figure 3 presented an example of Langley plot. The correlation coefficient R^2 is a quantity that gives the quality of a least squares fitting to the measured data. The correlation coefficient R^2 measured the strength and the direction of a linear relationship between two variables. A perfect correlation of R^2 is 1 achieved only when all data points lied exactly on a straight-line A correlation coefficient greater than 0.9 is generally described a strong relation between the two variables.

The result of estimated value of ultraviolet broadband intensity contrasted with the identical measured data over 2014 and 2015. The outcomes were listed in Table 3 and 4 showed the data of ultraviolet measured UV-M and ultraviolet estimated UV-S. These tables also presented the statistical test such as MBE, RMSE and RMSE (%), for each month during the study period. It is clear that the estimated amount of UV radiation is in perfect covenant with the measured amount in the year and therefore, validate our analysis. This is demonstrated by the relatively low values of the statistical parameters investigated, (MBE, RMSE and RMSE (%)). The root

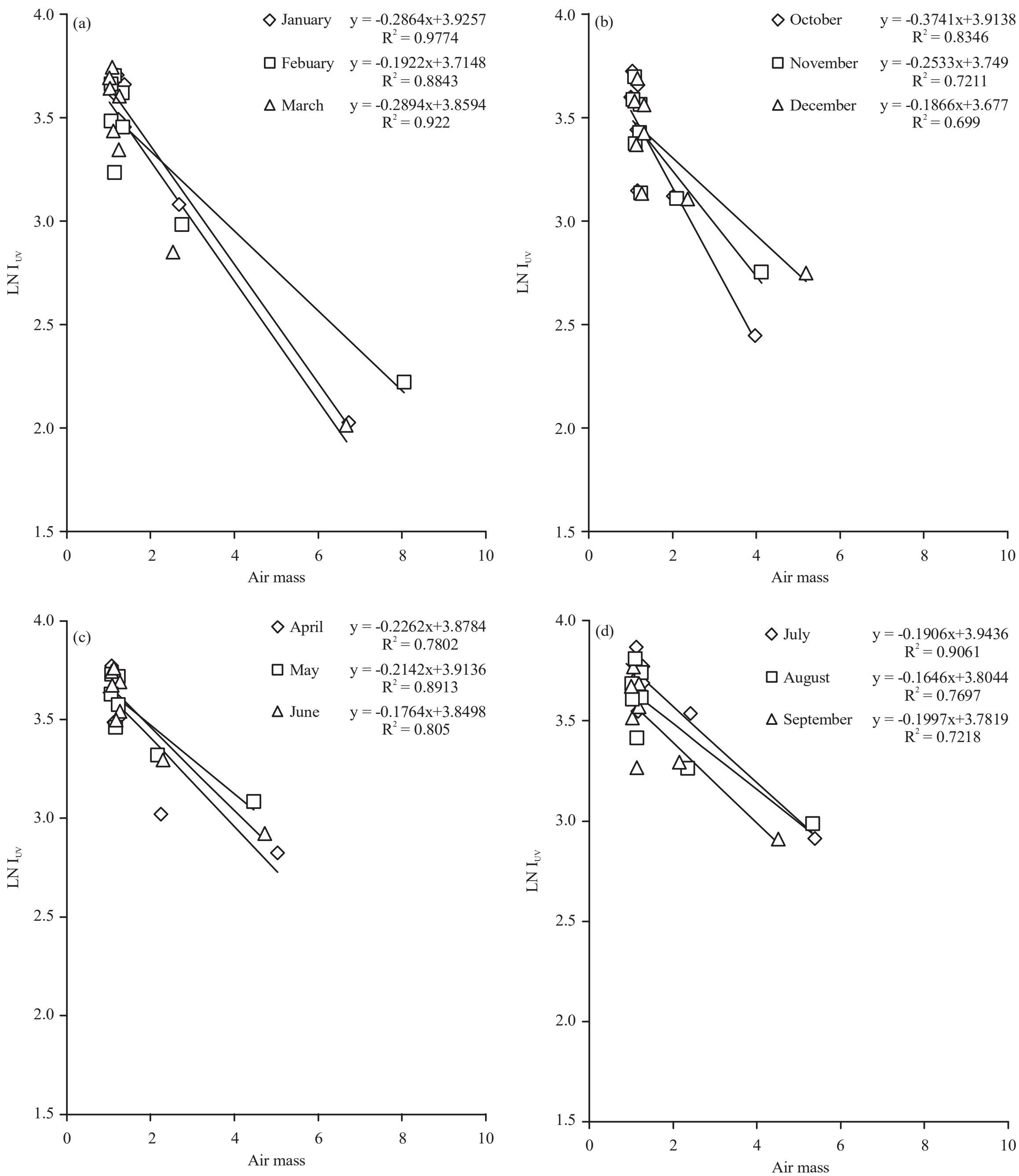

Fig. 3(a-d): Langley plot for UV broadband radiation intensity and respective liner function for 2014 in Bangi, Malaysia, (a) First quarter, (b)Fourth quarter shows the wet season, (c) Second quarter and (d) Third quarter shows the dry season

means square error (RMSE) measured the size of the variation between the evaluated and measured data of 2014 and 2015. It is ranged between 0 and 1.3 for 2014 and almost 0 for 2015. Low (RMSE) value is desirable. The mean bias error (MBE) negative indicated that the estimate values underestimated the measured value. On the other hand, the positive MBE indicated that the estimate values overestimated the measured value which is presented in 2014 and 2015 in Table 3 and 4. The RMSE (%) of corresponding values are also calculated to compare the computed values with the measured value. It is noted that the lowest percentage RMSE is 0.48% for July, while the highest percentage RMSE value is 2.66 for March in 2014. Meanwhile the lowest percentage RMSE value for 2015 is 0.04 in May. The relatively lower

Table 3: Comparison between the measured, UV-M Wm^{-2} and estimated, UV-S Wm^{-2}, values of ultraviolet radiation and the statistical parameters for monthly UV at Bangi, Malaysia during 2014

Months	UV-M	UV-S	RMSE	RMES (%)	MBE
January	30.97	38.47	0.52	1.76	1.03
February	26.39	33.97	0.49	1.65	0.88
March	27.19	36.56	0.50	1.72	0.91
April	31.48	39.11	0.52	1.77	1.05
May	32.84	39.65	0.52	1.79	1.10
June	32.76	40.48	0.53	1.81	1.09
July	38.44	40.11	0.53	1.80	1.28
August	31.65	38.04	0.51	1.75	1.06
September	29.94	35.75	0.50	1.70	1.00
October	26.90	34.63	0.49	1.67	0.90
November	24.26	29.07	0.45	1.53	0.81
December	26.62	32.83	0.48	1.63	0.89

Table 4: Comparison between the measured, UV-M Wm^{-2} and estimated, UV-S Wm^{-2}, values of ultraviolet radiation and the statistical parameters for monthly UV at Bangi, Malaysia during 2015

Months	UV-M	UV-S	RMSE	RMES (%)	MBE
January	36.83	35.76	0.09	0.23	0.09
February	38.57	38.37	0.02	0.04	0.02
March	38.52	37.89	0.05	0.13	0.05
April	40.35	39.56	0.07	0.17	0.07
May	35.65	35.48	0.01	0.04	0.01
June	39.46	39.02	0.04	0.10	0.04
July	42.84	42.16	0.06	0.15	0.06

RMSE (%) values in Table 3 and 4 occurred during the peak radiation months which may be attributed to the clear sky conditions for these months. Additionally, the mathematical expressions could be applied to estimate the solar ultraviolet intensity at any location of Malaysia or other difficulties encountered in measuring of UV irradiance.

CONCLUSION

This study has characterized the broadband of solar ultraviolet (300-400 nm) spectral irradiance between 2014 and 2015 at Bangi, Malaysia. The measurement of UV radiation using Avantes AvaSpec spectrometer is less complicated, more compact and less costly. However, the highest and lowest values of UV are observed in the month of July and November. Moreover, the diurnal variation of UV broadband radiation intensity exhibits the same trend for all measured data. Finally, our measured UV is validated using estimated UV from mathematical model and the statistical analysis confirmed the high correlation between those two readings. The mathematical model could be used to reliably estimate UV radiation at any other location where there are no measured data of UV radiation or their difficulties encountered in characterizing of UV radiation. Nevertheless, a reliable calibration of the instrument is required to compare results from different observation sites.

SIGNIFICANCE STATEMENT

This study detects an accessible method to measure the direct radiation of solar ultraviolet spectral irradiance in Bangi, Malaysia, that can be beneficial for characterizing the UV intensity in the ground level and design of certain solar energy application. Moreover, the UV intensity has been compared with other observation site. Therefore, the international scientific community can form global ultraviolet climatology picture. This study also will help researcher to forecasting the UV intensity at solar noon by using the mathematical model.

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