Research Article

Science, Engineering and Health Studies
https://li01.tci-thaijo.org/index.php/sehs
ISSN (Online): 2630-0087

Development of empirical models for calculating global and diffuse erythemal weighted solar ultraviolet radiation under clear sky conditions in Thailand

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***Received**: 27 March 2023*
***Revised**: 26 April 2024*
***Accepted**: 28 April 2024*
***Published**: 28 October 2024*

***Citation**:*
Laiwarin, P., Buntoung, S., and Janjai, S. (2024). Development of empirical models for calculating global and diffuse erythemal weighted solar ultraviolet radiation under clear sky conditions in Thailand. Science, Engineering and Health Studies, 18, 24020003.

ABSTRACT

This study introduced semi-empirical models for calculating hourly global and diffuse erythemal weighted ultraviolet (EUV) solar radiation under clear sky conditions in Thailand. To develop these models, global and diffuse erythemal ultraviolet data collected over a decade (2011–2020) from four solar monitoring stations situated in the main regions of Thailand were used. The data was classified into two groups. The first group (2011–2018) was used for modeling, while the second group (2019–2020) was reserved for model validation. The global and diffuse EUV radiation models revolve around semi-empirical functions. These functions express both types of EUV radiation in terms of normalized variables, specifically the total ozone column, aerosol optical depth, and air mass. To assess the accuracy of the proposed models, their outputs for hourly global and diffuse EUV radiation were calculated at the four monitoring stations. These outputs were then compared against actual measurements to validate the effectiveness of the models. The evaluation revealed a root mean square difference of 15.8% for global EUV radiation and 14.9% for diffuse EUV radiation when compared to the mean measured values.

Keywords: global erythemal ultraviolet radiation; diffuse erythemal ultraviolet radiation; empirical model; clear sky

1. INTRODUCTION

Solar ultraviolet (UV) radiation constitutes a small part of the solar spectrum, comprising UVA (320–400 nm), UVB (280–320 nm), and UVC (100–280 nm). The atmosphere absorbs all UVC and a major part of UVB radiation (El-Nouby Adam and El Shazly, 2007). Consequently, only the UVA and some parts of UVB reach the surface of the Earth, with their levels strongly influenced by atmospheric parameters, such as clouds, ozone, and aerosols (Scaglione et al., 2016; Villán et al., 2010). Erythemal weighted solar ultraviolet (EUV) radiation is the term used for UV radiation adjusted for the erythemal response of human skin. This measurement is generally used to indicate the impact of solar UV radiation on human health through the UV index (WHO, 2002). In general, the maximum EUV radiation levels on the surface of the Earth occur under clear sky conditions at any given time and location, making it a benchmark for several solar radiation calculations. Therefore, collecting information on EUV radiation under clear sky conditions is essential. Like other solar radiation bands, EUV radiation is composed of direct and diffuse components, collectively referred to as global EUV radiation (Dombrovsky et al., 2011). Although global EUV and diffuse EUV radiation under clear sky conditions can be calculated using different radiative transfer models (Mateos et al., 2010), these calculations are usually complex and require extensive model input data that may not always be available. To address this issue, several researchers have developed simpler empirical models for EUV radiation calculations.

Nunez et al. (2002) created an empirical model for calculating global EUV radiation under clear sky conditions using data from Tasmania, Australia. Their model expressed global EUV radiation as a linear function of the solar zenith angle and total ozone column. Bilbao et al. (2015) formulated a similar model based on global EUV solar radiation measurements at Marsaxlokk, Malta. Nevertheless, these studies did not account for aerosols, limiting their models' applicability to atmospheres with low aerosol concentrations. Kudish and Evseev (2020) proposed an empirical model for estimating hourly EUV based on broadband global irradiation, correlating it with the clearness index in Israel. The validation results indicated a root mean square difference (RMSD) ranging between 18.49% and 19.80%.

To the best of our knowledge, no models currently exist for calculating diffuse EUV radiation under clear sky conditions. Although there are models for computing global EUV radiation under clear sky conditions, they are not appropriate for use in Thailand, known for its high aerosol content. Therefore, this study seeks to develop models for calculating global and diffuse EUV solar radiation under clear sky conditions using EUV solar radiation and atmospheric data, including aerosols in Thailand.

2. MATERIALS AND METHOD

2.1 Materials

Various data sets were used in this study. The details of these data sets are explained below.

2.1.1 Global and diffuse EUV solar radiation

Our research group established solar monitoring stations across four main regions of Thailand to obtain solar radiation and atmospheric data for our studies on atmospheric and solar energy. These regions included the Chiang Mai station (CM; 18.78°N, 98.98°E) in the northern region, Ubon Ratchathani station (UB; 15.25°N, 104.87°E) in the northeastern region, Nakhon Pathom station (NP; 13.82°N, 100.04°E) in the central region, and Songkhla station (SK; 7.2°N, 100.60°E) in the southern region (Figure 1). Both global and diffuse EUV solar radiation were measured at these stations. At each station, a broadband UV instrument (Solar Light, model 501A) was installed on a pole at a height of 1.8 m on the rooftop of the station building to measure the global EUV solar radiation (Figure 1A). Voltage signals from the instrument were captured every second using a datalogger (Yokogawa, model DX2000). To measure diffuse EUV radiation, a broadband UV instrument of the same model was mounted on a sun tracker (Kipp&Zonen, model 2AP) equipped with a shaded ball to block the direct UV component (Figure 1B). The voltage signals from the UV broadband instrument were captured every second by the same datalogger used to record the global EUV radiation. These voltage signals were then converted into EUV radiation measurements in mW/m^2 using the standard procedure proposed by Webb et al. (2006). The data were then simply averaged into hourly EUV radiation. The hourly EUV data were collected from 7 a.m. to 5 p.m., between January 2011 and December 2020 for this study.

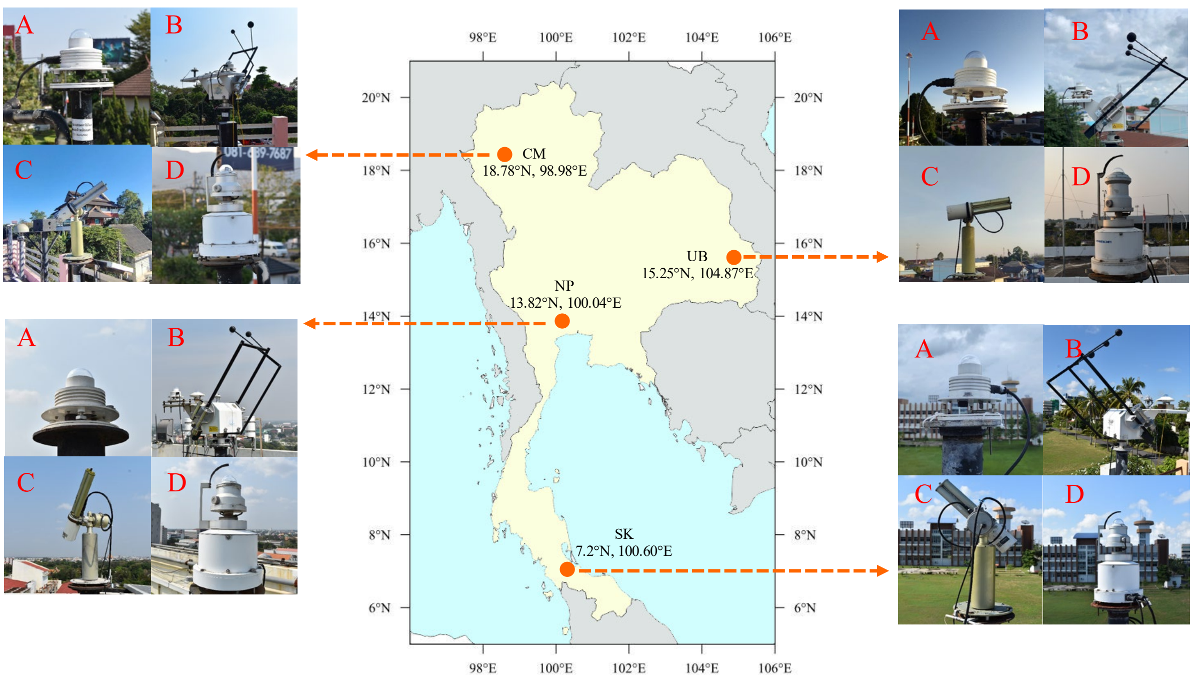

Figure 1. Instruments and locations across the four monitoring sites: (A) UV instruments for measuring global EUV, (B) UV instruments for measuring diffuse EUV, (C) sun photometers, and (D) skyviews

2.1.2 Ozone data set

Ozone is important for calculating EUV radiation at the surface of the Earth as it absorbs a significant portion of UV radiation. Therefore, in this study, daily total ozone column (O_3) data were acquired from the OMI/AURA satellite and were accessible for download from ftp://tom.gsfc.nasa.gov/pub/omi/data/ozone/ during the study period. The data for the four stations were extracted and used for modeling development and validation.

2.1.3 Aerosol data set

Aerosols significantly affect EUV radiation because they can scatter and absorb the radiation, especially in highly polluted regions such as in many parts of Thailand (Janjai et al., 2012). A sun photometer (Cimel, model CE-318) was installed at each solar monitoring station to measure aerosol optical properties (Figure 1C). The data collected by the sun photometer were submitted automatically to the Aerosol Robotic Network (AERONET) as part of a collaboration. Once processed by AERONET, the aerosol optical properties became available for download from https://aeronet.gsfc.nasa.gov/ for the locations of interest. This study extracted aerosol optical depth (AOD) at a wavelength of 340 nm that affects UV radiation. All data points were averaged to obtain hourly AOD data for this study.

2.1.4 Sky image data set

In this study, a skyview (Prede, model PSV-100) was installed at each station (Figure 1D) to capture an image of half of the celestial spheres every 5 minutes. These images provided measurements of cloud cover of the fraction of clouds in the sky, measured in the okta unit. The cloud cover was used to classify sky conditions into five classes: clear sky (<1 oktas), few clouds (1–2 oktas), scattered clouds (3–4 oktas), broken clouds (5–7 oktas), and overcast sky (8 oktas) (Grant and Gao, 2003). Therefore, in this study, data corresponding to a cloud cover of 0 were selected as representative of clear sky conditions.

2.1.5 Air mass data set

The atmospheric path that the solar radiation traverses to reach the surface of the Earth is described by the air mass concept. Air mass is calculated using Equation 1 (Gueymard, 1993):

$$m_a = m_r\left(\frac{P}{101.325}\right) \tag{1}$$

where P denotes the atmospheric pressure (kPa), m_a represents the air mass at mean sea level (unitless), m_r signifies the relative air mass (unitless) and can be calculated from Equation 2 presented by Kasten (1965):

$$m_r = [\cos\theta_z + 0.15(93.885 - \theta_z)^{-1.253}]^{-1} \tag{2}$$

where θ_z indicates the solar zenith angle (degree).

From Equation 1, P can be obtained using Equation 3, as presented by Lunde (1980):

$$\frac{P}{P_0} = \exp(-0.0001184Z) \tag{3}$$

where P_0 denotes the standard pressure (101.325 kPa), and Z represents the height from mean sea level (m).

2.2 Method

The hourly global and diffuse EUV solar radiation, AOD, air mass, and daily total ozone column under clear sky conditions were acquired for this study. The data span from 2011 to 2020 and were divided into two groups. The first group contains data from 2011 to 2018, which was used for modeling, while the second group, consisting of data from 2019 to 2020, was used for model validation. For the modeling processing, each data set was normalized against its maximum value to standardize the range of input data between 0 and 1. Using the Statistica program, the relationship between the normalized EUV radiation and other atmospheric parameters was analyzed to derive coefficients for empirical models. For model validation, the calculated global EUV and diffuse EUV solar radiation values were compared with measured EUV solar radiation data. Then, the differences between these data sets were quantified using RMSD and mean bias difference (MBD), as shown in Equation 4 and Equation 5, respectively.

$$\mathrm{RMSD} = \frac{\sqrt{\frac{\sum_{i=1}^{N}\left(EUV_{model,i}-EUV_{meas,i}\right)^2}{N}}}{\frac{\sum_{i=1}^{N} EUV_{meas,i}}{N}} \times 100\% \tag{4}$$

$$\mathrm{MBD} = \frac{\frac{\sum_{i=1}^{N}\left(EUV_{model,i}-EUV_{meas,i}\right)}{N}}{\frac{\sum_{i=1}^{N} EUV_{meas,i}}{N}} \times 100\% \tag{5}$$

where $EUV_{model,i}$ denotes the solar EUV radiation under clear sky conditions calculated from the model, $EUV_{meas,i}$ indicates the solar EUV radiation under clear sky conditions derived from measurements, and N signifies the number of data points.

3. RESULTS AND DISCUSSION

3.1 Empirical models

In this study, two empirical models were proposed for estimating EUV radiation under clear sky conditions: one for global EUV radiation and the other for diffuse EUV radiation. The details of each model are listed below.

The input data for the models were selected based on atmospheric compositions and geometric parameters that influence global EUV and diffuse EUV solar radiation at the Earth's surface. Therefore, in this study, total column ozone, AOD, and atmospheric air mass were incorporated into the models.

Using the Statistica program to identify the best relationship between hourly global EUV radiation and related atmospheric parameters, the model for estimating the hourly global EUV obtained in this study is presented in Equation 6:

$$\frac{EUV_g}{EUV_{g\,max}} = a_0 + a_1 e^{\left(a_2\frac{O_3}{O_{3\,max}}+a_3\frac{AOD_{340}}{AOD_{340\,max}}\right)\frac{m_a}{m_{a\,max}}} \tag{6}$$

where EUV_g denotes the global solar EUV radiation under clear sky conditions (mW/m²), $EUV_{g\,max}$ represents the maximum global solar EUV radiation under clear sky conditions (400 mW/m²), O_3 indicates the total ozone column (cm), $O_{3\,max}$ signifies the maximum total ozone column (0.320 cm), AOD_{340} presents the AOD at a 340nm wavelength (unitless), $AOD_{340\,max}$ denotes the maximum AOD at a 340nm wavelength that is equal to 5. Furthermore, m_a denotes air mass (unitless) and $m_{a\,max}$

represents the maximum air mass that is equal to 20. The model coefficients were denoted as a_0, a_1, a_2, and a_3: a_0 = 0.0380, a_1 = 5.7345, a_2 = −50.1048, and a_3 = −36.3765. These coefficients have a 95% confidence level.

From the resulting model, the coefficients a_2 and a_3 are negative values, indicating that an increase in atmospheric ozone or aerosols in the atmosphere can cause a decrease in global EUV radiation. Conversely, an increase in air mass results in a decrease in global EUV radiation.

Similarly, the optimal relationship between hourly diffuse EUV radiation under clear sky conditions and the related parameters was obtained in this study. The model for estimating hourly diffuse EUV radiation is presented in Equation 7:

$$\frac{EUV_d}{EUV_{d\,max}} = a_0 + a_1\frac{O_3}{O_{3\,max}} + a_2\frac{AOD_{340}}{AOD_{340\,max}} + a_3\left(\frac{m_a}{m_{a\,max}}\right)^{a_4} \quad (7)$$

where EUV_d denotes the diffuse EUV radiation under clear sky conditions (mW/m²) and $EUV_{d\,max}$ represents the maximum diffuse solar EUV radiation under clear sky conditions (300 mW/m²). a_0, a_1, a_2, a_3, and a_4 denote the model coefficients: a_0 = 0.3051, a_1 = −0.3488, a_2 = −0.2784, a_3 = 0.0018, and a_4 = −1.9211. These coefficients also have a 95% confidence level.

The formula for calculating diffuse EUV radiation differs from that for calculating the global EUV radiation. However, the effects indicated by the coefficients are similar. Atmospheric ozone, aerosols, and air mass can attenuate diffuse EUV solar radiation.

3.2 Validation results

The model performances were evaluated by comparing the UV irradiance estimates produced by the models with those obtained from ground-based measurements using independent data sets.

The comparison of hourly global EUV irradiances between the proposed model and the ground-based measurements at the four monitoring sites is shown in Figure 2. The differences between the two data sets in terms of RMSD and MBD are 15.8% and −5.5%, respectively. The validation results for the diffuse EUV radiation are presented in Figure 3, where the RMSD and MBD are 14.9% and 1.1%, respectively.

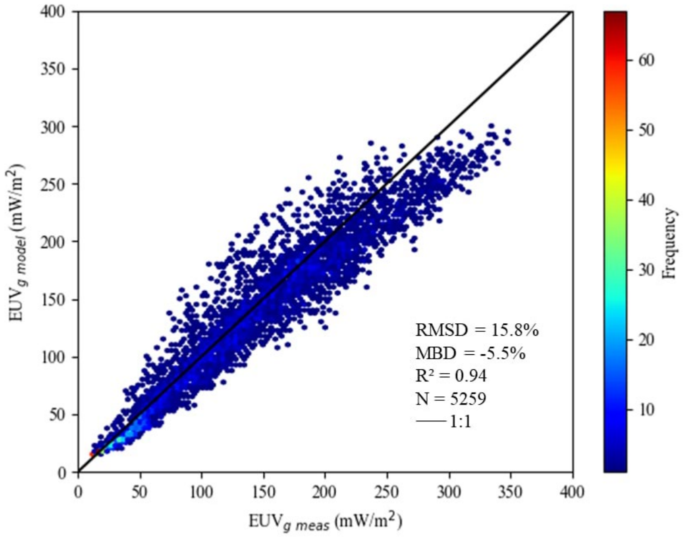

Figure 2. Comparison between global EUV solar radiation from the model ($EUV_{g\,model}$) and the measurements ($EUV_{g\,meas}$)

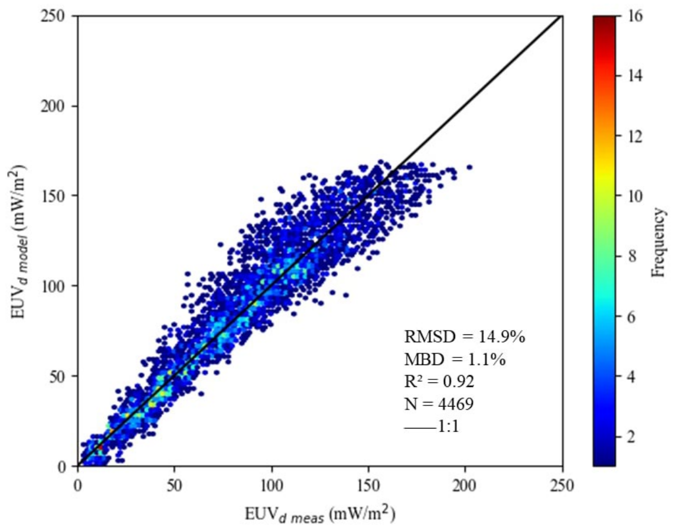

Figure 3. Comparison between diffuse EUV solar radiation from the model ($EUV_{d\,model}$) and the measurements ($EUV_{d\,meas}$)

Our results show that the models for estimating hourly global EUV and diffuse EUV radiation performed well compared with those derived from ground-based measurements. The data points densely populated around the 1:1 line for both global and diffuse EUV radiation, as seen in Figures 2 and 3. A notable observation was the underestimation of global EUV radiation obtained from the model at higher EUV values, especially from the Songkhla site, which exhibited different climate conditions compared to the other three sites. Despite this resulting in a higher MBD of −5.5%, the error margin is considered acceptable. Our proposed model for calculating global EUV radiation can be compared with the model reported by Bilbao et al. (2015), which estimated global EUV radiation under cloudless conditions in the Marsaxlokk (Malta) campaign with low aerosol loads using only two input data: solar zenith angle and total column ozone. We adjusted the coefficients of Bilbao's model using our data set to test its performance in our region. The differences in terms of RMSD and MBD between the global EUV obtained from Bilbao's model and our measurements were 23.4% and −7.2%, respectively; their values were higher than those from our models. Therefore, the models proposed in this study are better suited for the Thai region that is characterized by high aerosol loads.

4. CONCLUSION

This research developed empirical models to calculate the global and diffuse EUV solar radiation under clear sky conditions using total ozone column, AOD at 340 nm, and air mass as input variables. The results demonstrate that the estimations of global and diffuse EUV solar radiation from the models are consistent with measurements, exhibiting a RMSD of 15.8% for global and 14.9% for diffuse EUV radiation, respectively, and a MBD of −5.5% for global and 1.1% for diffuse EUV radiation, respectively. These findings indicate that the models can calculate global and diffuse EUV solar radiation in tropical regions such as in Thailand.

ACKNOWLEDGMENT

The authors thank the Meteorological Departments of Thailand at Chiang Mai, Ubon Ratchathani, and Songkhla for the maintenance of our instruments at the sites. The authors are also grateful to the AERONET team for providing aerosol data.

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