DEVELOPMENT OF A MODEL FOR CALCULATING GLOBAL SPECTRAL SOLAR IRRADIANCE UNDER ALL-SKY CONDITIONS IN THAILAND

By
MISS Sunisa KHAKHU

A Thesis Submitted in Partial Fulfillment of the Requirements
for Doctor of Philosophy PHYSICS
Department of PHYSICS
Silpakorn University
Academic Year 2022

การพัฒนาแบบจำลองสำหรับคำนวณหาสเปกตรัมรังสีรวมจากดวงอาทิตย์ภายใต้สภาพท้องฟ้าทั่วไปในประเทศไทย

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Title	Development of a model for calculating global spectral solar irradiance under all-sky conditions in Thailand
By	MISS Sunisa KHAKHU
Field of Study	PHYSICS
Advisor	Professor Serm Janjai, Ph.D.

Faculty of Science, Silpakorn University in Partial Fulfillment of the Requirements for the Doctor of Philosophy

.... Dean of Faculty of Science
(Assistant Professor Narong Chimpalee, Ph.D.)

Approved by

.... Chair person
(Assistant Professor Itsara Masiri, Ph.D.)

.... Advisor
(Professor Serm Janjai, Ph.D.)

.... Committee
(Assistant Professor Rungrat Wattan, Ph.D.)

.... Committee
(Assistant Professor Korntip Tohsing, Dr.rer.nat.)

.... External Examiner
(Assistant Professor Pranomkorn Choosri, Ph.D.)

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MISS Sunisa KHAKHU : Development of a model for calculating global spectral solar irradiance under all-sky conditions in Thailand Thesis advisor : Professor Serm Janjai, Ph.D.

This thesis presents a model for computing global spectral solar irradiance under all-sky conditions in Thailand. The model expresses the global spectral irradiance under all- sky conditions as a multiplication of two functions, namely a function of global spectral irradiance under clear sky conditions and a cloud modification function. To create the model, global spectral solar irradiance was measured at four stations in main regions of Thailand, namely Chiang Mai (18.77˚ N, 98.97˚ E) in the northern region of Thailand, Ubon Ratchathani (15.25˚ N, 104.87˚ E) in the north-eastern region of the country, Nakhon Pathom (13.82˚ N, 100.04˚ E) in the central region of this country, and Songkhla (7.18˚ N, 100.60˚ E) in the southern region of Thailand. The spectral data from these stations were collected and then separated into two groups. The first group (January, 2017- December, 2020) was employed for modeling and the second group (January- December, 2021) for validating the model. The first function was constructed using the first group of data. Clear sky conditions were identified by using sky images obtained from a sky camera installed at each station. To build the second function, satellite-derived cloud index obtained from Himawari-8 image data at the stations was used. To validate the model of the global spectral solar irradiance under all-sky conditions, the model was used to compute the global spectral solar irradiance at the four stations for the year 2021 and the result was compared to the global spectral solar irradiance obtained from measurements at the four stations. It was found that the spectral irradiance calculated from the model agreed well with those obtained from the measurements with the discrepancy in terms of root mean square difference relative to the mean measured value (RMSD) of 9.48%. We concluded that the model performed well in calculating global spectral solar irradiance.

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Chapter1

Introduction

1.1 Rationale

The global spectral solar irradiance is of importance for research and applications of solar cells because each solar cell has different responses to each wavelength of solar radiation (Green, 1982). The global spectral solar irradiance is also essential for research and applications of selective surface systems (Duffie et al., 2020) as the systems have wavelength response to the solar spectrum. Spectral models could be divided into two categories namely, spectral models for clear sky conditions and spectral models for all-sky conditions. This study is emphasized on the development of a spectral model for all-sky conditions. This is because all-sky conditions are real conditions for most of applications. Although information on global spectral solar irradiance could be obtained from measurements, global spectral solar irradiance is scarce due to high cost of the measuring equipment. Most data on global spectral solar irradiance are practically obtained from modeling approaches. Most global spectral solar irradiance models are for clear sky conditions (Bird, 1984; Bird & Riordan, 1986; Gueymard, 2001; Gueymard & Kocifaj, 2022; Jacovides et al., 2004; Khakhu et al., 2022; Koussa et al., 2017; Leckner, 1978; Madkour et al., 2006). To the best of our knowledge, there is no simple model for calculating global spectral solar irradiance under all-sky conditions. Therefore, the objective of this study is to develop a model for computing global spectral solar irradiance under all-sky conditions for Thailand, a tropical country in South-east Asia. The country has high relative humidity in the wet season (Buntoung et al., 2021) and high aerosol load in the dry season (Janjai et al., 2012).

1.2 Objectives

1. To develop an empirical model for calculating global spectral solar iradiance under all-sky conditions in Thailand.
2. To validate the empirical model.

1.3 Research Hypothesis

Spectral solar irradiance enters the Earth's surface, but some will be reflected into outer space. The reflected solar radiation can be measured using satellites. The portion of solar radiation that travels through the atmosphere to the Earth's surface is absorbed and scattered by the atmospheric parameters, altering the solar spectrum. This change can be calculated from the amount of atmospheric constituents that solar radiation travels through. Based on the spectral values of extraterrestrial solar irradiance and their changes, a model can be built to determine the solar spectral value at the Earth's surface.

1.4 Scope of the study

This work proposed a model for calculating global spectral solar irradiance under all-sky conditions. To develop the model, global solar spectral irradiance was measured at Chiang Mai, Ubon Ratchathani, Nakhon Pathom and Songkhla during 2017-2020. The performance of the model was tested using data in year 2021.

Chapter 2

Theory and literature review

2.1 Solar radiation and spectral solar irradiance

The sun is the most important source of energy for humans and creatures on the earth. The radiation emitted by the sun is electromagnetic waves at various wavelengths, commonly known as solar radiation. Most components of solar radiation that reach the earth's surface are in the visible and infrared wavelength ranges that are directly used by humans and creatures in the form of natural light and heat, respectively. At present, there is more emphasis on renewable energy. Due to the past 30 years, the use of energy from fossil fuel sources has affected the environment. Therefore, researchers have conducted research to develop technologies for using energy from solar radiation or solar energy as an alternative to fossil fuel energy. More importantly, they have developed solar cells for solar power generation, solar water heaters, solar power plants and solar dryers, etc.

The radiation emitted by the sun is an electromagnetic wave with the wavelength ranging from gamma rays to radio waves. Each wavelength has a different intensity A graph or a table showing the relation between the intensity of the electromagnetic wave and the wavelength is called spectral solar irradiance or solar spectrum. When solar radiation enters the Earth's atmosphere, it is attenuated by scattering and absorption processes by atmospheric parameters, and varies with wavelength, thus altering the quality and quantity of incident solar spectra (Muneer, 2007). The knowledge of these spectral processes is very important for many scientific fields such as solar energy and biological applications (Gueymard, 2001).

2.1.1 Extraterrestrial spectral solar irradiance

The solar spectrum reaching the Earth's surface is actually a function of extraterrestrial solar spectrum and atmospheric constituents. This terrestrial spectrum is also important for many applications, such as earth-based photovoltaic systems and photosynthesis. There is a continuous emission and absorption of radiation varying from one area to another of the sun. Many researchers have been trying to determine the extraterrestrial solar spectrum. In 2000, the American Society for Testing and Materials (ASTM) developed an air mass zero reference solar spectrum (ASTM E-490). The ASTM E-490 solar spectral irradiance is based on data from satellites, space shuttle missions, high-altitude aircraft, rocket soundings, ground-based solar telescopes, and modeled spectral irradiance. The integrated spectral irradiance has been made to conform to the value of the solar constant is 1366.1 W/m^2. These data were generally accepted by scientific community (Duffie et al., 2020). The extraterrestrial spectral solar irradiance ASTM E-490 is shown in Figure 1. (https://www.nrel.gov/grid/solar-resource/spectra-astm-e490.html.)

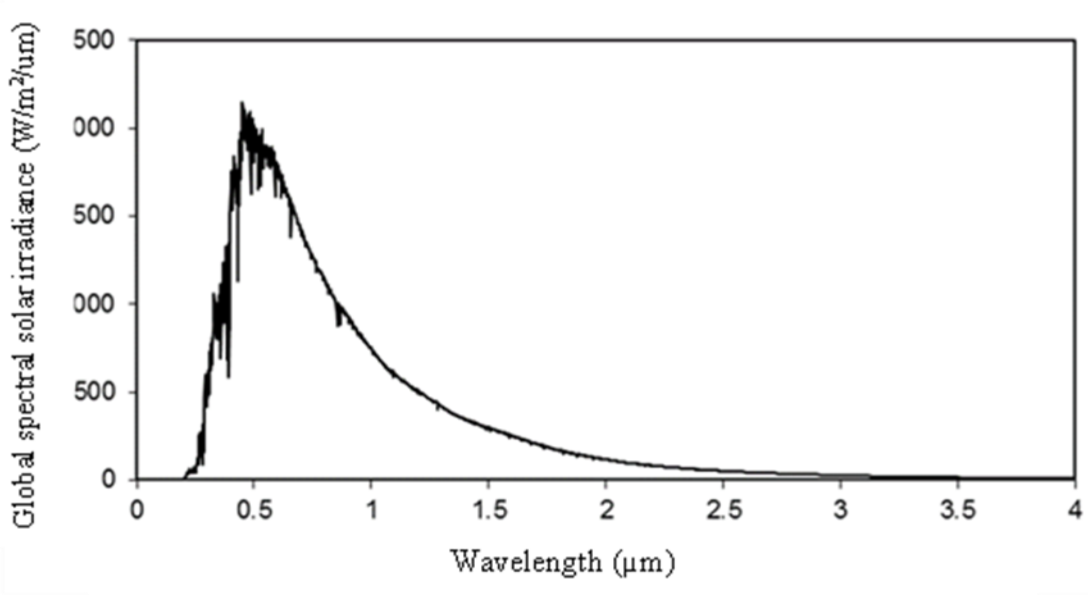

Figure 1 The extraterrestrial spectral solar irradiance ASTM E-490 (Adapted from ASTM, 2000).

2.1.2 Spectral solar irradiance at the earth's surface

The spectrum of solar radiation reaching the earth's surface depends on sky conditions. Sky conditions could be separated into three types: clear sky, partly cloudy sky, and overcast sky. For solar energy work, solar spectral data under all-sky conditions are generally required, that is it can be clear sky, partly cloudy sky or overcast sky. The solar spectral under clear sky conditions provides information about the maximum energy available for solar energy applications, therefore it can be used for calculating the solar spectral under all-sky conditions. The spectral solar irradiance reaching the earth's surface consists of two main components: direct spectral irradiance and diffuse spectral irradiance, the sum of direct spectral irradiance and diffuse spectral irradiance on a horizontal surface is global spectral irradiance. When solar radiation enters the earth's atmosphere, it is attenuated by scattering and absorption processes by atmospheric parameters, altering the solar spectrum. This change can be calculated from the amount of atmospheric constituents that solar radiation travels through, it is necessary to study various atmospheric components that affect the spectral solar irradiance. In addition, some of the spectral solar irradiance will be reflected by the earth's surface through the atmosphere to outer space again. As shown in Figure 2, we can measure the reflected spectral solar irradiance by satellites.

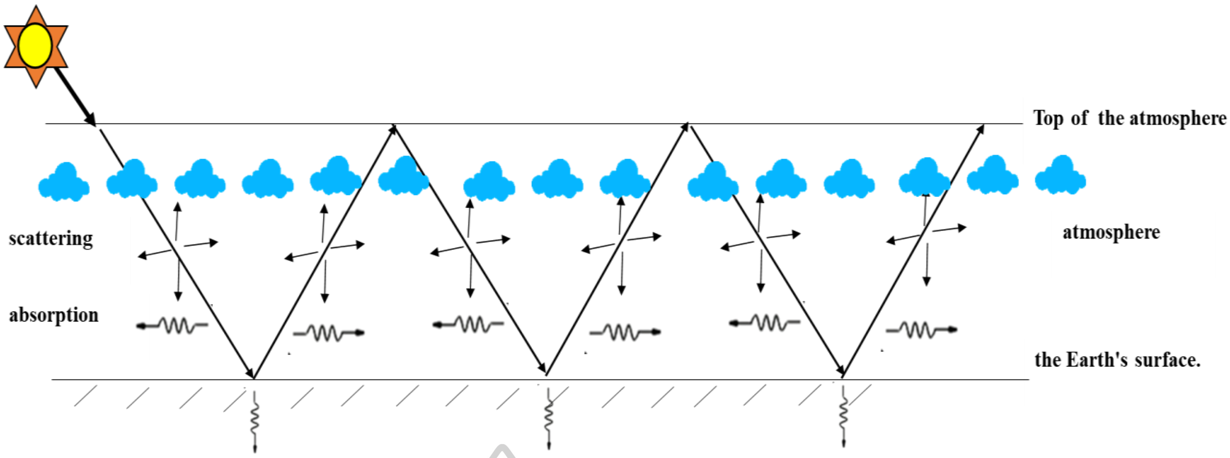

Figure 2 Attenuation of spectral solar irradiance. (Adapted from Iqbal, 1983)

The optical depth of atmospheric parameters determines the ability to attenuate solar radiation traveling through the atmosphere by absorption and scattering processes, thereby reducing the spectral solar irradiance. Therefore, it is necessary to study the atmospheric parameters that affect the attenuation of the spectral solar irradiance and to be able to determine the spectral solar irradiance at the Earth`s surface. The details of each process are described as follows.

2.1.2.1 Scattering due to air molecules.

The scattering of air molecules in the atmosphere can be explained by Rayleigh's theory. Rayleigh's theory assumes that the scattering particles are spherical. This theory can be applied to study the scattering of spectral solar irradiance by air molecules, which are gas molecules in the atmosphere. This is called Rayleigh scattering. The property of air molecules to be attenuated by scattering is usually described in terms of optical depth by Rayleigh scattering. The optical depth of air molecules scattering is the result of spectral solar irradiance scattered in relation to wavelength (Brine & Iqbal, 1983). The equation is written as:

$$\tau'_{R\lambda} = 0.008735\lambda^{-4.08} \tag{2.1}$$

where $\tau'_{R\lambda}$ = the optical depth of air molecules scattering (-)

λ = wavelength (μm)

The attenuation of spectral solar irradiance from scattering by air molecules can be expressed in terms of transmittance, which depends on the optical depth of air molecules scattering and the air mass (Leckner, 1978). The spectral transmittance by air molecules can be calculated empirically using the equation given by Leckner (1978). The equation is written as:

$$\tau_{R\lambda} = \exp(0.008735\lambda^{-4.08} m_a) \quad (2.2)$$

where $\tau_{R\lambda}$ = spectral transmittance by air molecules (-)

m_a = the air mass (-)

λ = wavelength (μm)

Equation (2.2) is plotted in Figure 3, show the influence of the spectral transmittance by air molecules at each wavelength for air mass equal 1, 3, and 5 (Iqbal, 1983).

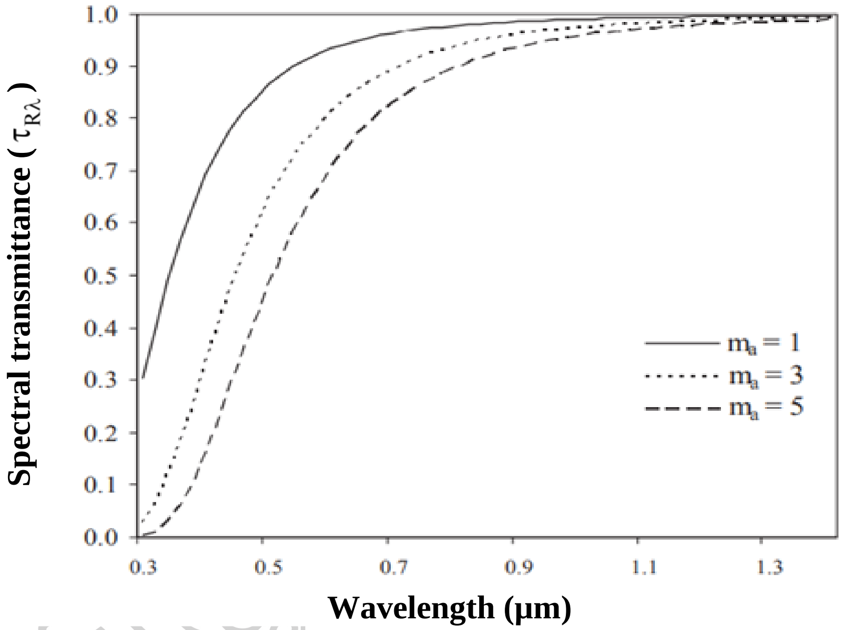

Figure 3 The spectral transmittance by air molecules as a function of air mass. (Adapted from Iqbal, 1983)

2.1.2.2 Scattering due to aerosols.

Aerosols are very small solid particles or very small liquid droplets suspended in the atmosphere, excluding clouds and precipitation. The aerosol particle sizes range from 0.1-1000 μm, which different shapes and chemical compositions depending on the source of aerosols (Thomas & Stamnes, 2002).

The attenuation of spectral solar irradiance is due to scattering or absorption, or by both processes from aerosols, spectral solar irradiance is scattered by aerosols causing diffuse spectral irradiance and some will be absorbed by aerosols. However, aerosols can attenuate the solar spectrum by both processes, scattering and absorption processes, it is difficult to separate the fraction of the reduced solar radiation from each process (Iqbal, 1983). Ångström suggests an equation for calculating aerosol optical depth, known as Ångström turbidity formula (Ångström, 1929). This equation depends on Ångström turbidity coefficient, Ångström wavelength exponent, and wavelength. The equation is written as:

$$\tau'_{aer,\lambda} = \beta\lambda^{-\alpha} \quad (2.3)$$

where $\tau'_{aer,\lambda}$ = aerosol optical depth (-).

β = Ångström turbidity coefficient (-).

α = Ångström wavelength exponent (-).

Spectral transmittance due to aerosols was estimated by using the aerosol optical depth, from equation 2.3. The equation is written as:

$$\tau_{aer,\lambda} = \exp(\beta\lambda^{-\alpha}m_a) \quad (2.4)$$

where $\tau_{aer,\lambda}$ = spectral transmittance due to aerosols (-).

m_a = the air mass (-).

Figure 4 shows the relationship between spectral transmittance due to aerosols at each wavelength and air mass, with a number of β and α are 0.2 and 1.3, respectively. From the Figure 4 shows that aerosols affect the spectral solar irradiance at short wavelengths (Iqbal, 1983).

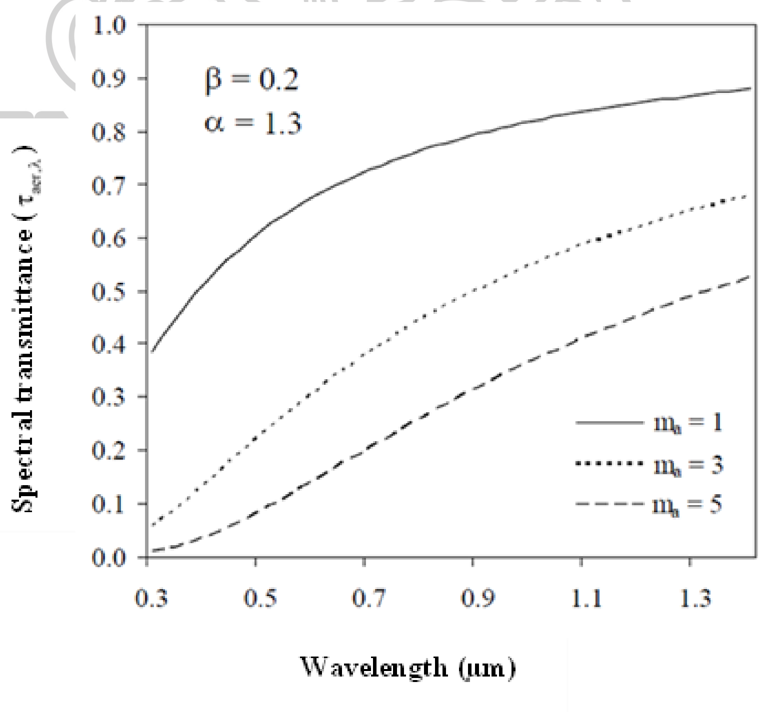

Figure 4 Spectral transmittance due to aerosols at each wavelength and air mass, with a number of β and α are 0.2 and 1.3, respectively. (Adapted from Iqbal, 1983)

2.1.2.3 Absorption due to water vapor

Water vapor is the gaseous phase of water that permeates the spaces between other gas molecules in the atmosphere. Depending on temperature and pressure of the atmosphere, water vapor changes into a liquid or solid state. The method for determining the amount of water vapor in solar radiation is usually expressed in terms of precipitable water, in centimeter.

In the near-infrared spectrum, water vapor is the most important absorber. Accurate determination of transmittance is therefore of importance in the solar spectral irradiance model. Calculating the solar spectral irradiance at the Earth's surface requires the solar radiation transmission coefficient at each wavelength, which depends on the amount of water vapor and the extinction coefficient of water vapor. Spectral transmittance caused by water vapor absorption was calculated using an empirical formula proposed by Leckner (1978). The equation is written as:

$$\tau_{w\lambda} = \exp[-0.2385 k_w w m_r / (1 + 20.07 k_{w\lambda} w m_r)^{0.45}] \tag{2.5}$$

where $\tau_{w\lambda}$ = spectral transmittance caused by water vapor (-).

k_w = extinction coefficient of water vapor (cm^{-1}).

w = the amount of water vapor in from precipitable water (cm).

m_r = relative air mass (-).

An example of spectral transmittance caused by water vapor in the case w=2 cm is shown in Figure 5, which can be clearly seen that water vapor is the most important absorber in NIR wavelength range.

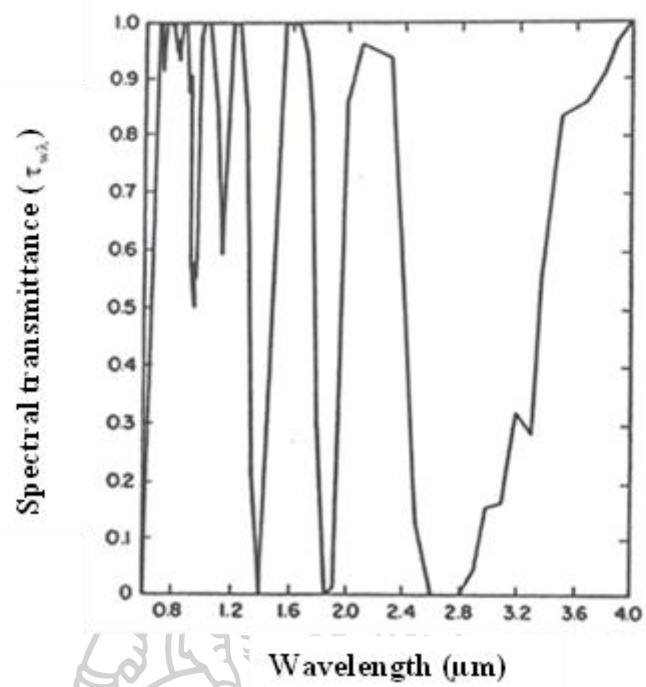

Figure 5 Spectral transmittance caused by water vapor, in the case w=2 cm. (Adapted from Iqbal, 1983)

2.1.2.4 Absorption due to ozone

Ozone (O_3) is a highly reactive gas composed of three oxygen atoms. It is both a natural and a man-made product that occurs in the stratosphere and the troposphere. The method for determining the amount of ozone in solar radiation is usually expressed in terms of an atmospheric column, in centimeter, which is similar to the amount of water vapor.

Ozone absorbs strongly in the UV, moderately in the VIS, and slightly in NIR. From the energy level structure of the ozone molecule, ozone can absorb into 3 wavelength bands which are Hartley band (0.22-0.295 µm), Huggins band (0.32-0.65 µm), Chappuis band (0.45-0.65 µm) (Vigroux, 1953). The optical depth of ozone is used as a value that shows the ability of ozone to absorb the solar spectral irradiance, it was calculated using an equation (2.6), proposed by Vigroux (1953). The equation is written as:

$$\tau'_{o,\lambda} = -k_{0\lambda}\ell \tag{2.6}$$

where $\tau'_{o,\lambda}$ = the optical depth of ozone (-).

$k_{0\lambda}$ = extinction coefficient of ozone (cm^{-1}).

ℓ = the amount of ozone (cm).

Spectral transmittance due to ozone was estimated by using the optical depth of ozone, from Equation (2.6). The equation is written as:

$$\tau_{o,\lambda} = \exp(-k_{0\lambda}\ell m_r) \tag{2.7}$$

where $\tau_{o,\lambda}$ = spectral transmittance caused by ozone (-).

m_r = relative air mass (-).

An example of spectral transmittance caused by ozone at each wavelength is shown in Figure 6.

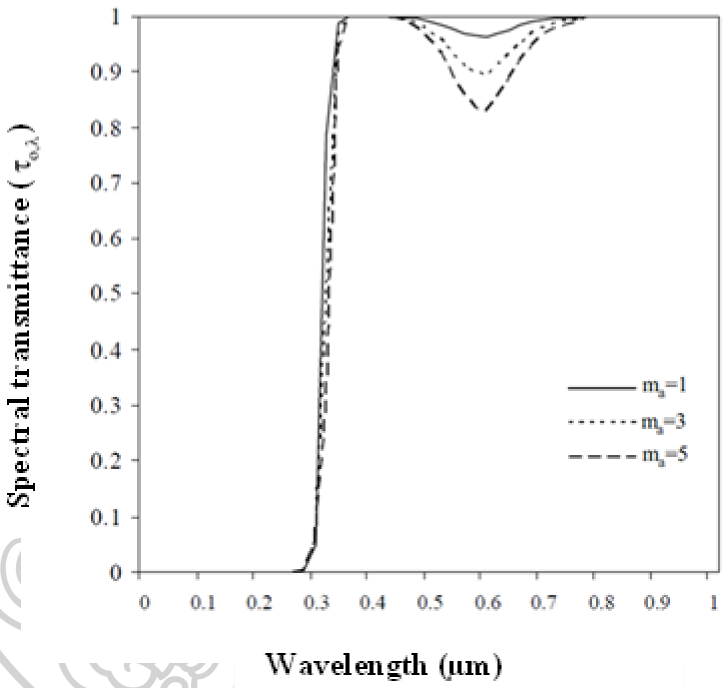

Figure 6 Spectral transmittance caused by ozone at each wavelength.
(Adapted from Iqbal, 1983)

2.1.2.5 Absorption due to nitrogen dioxide

Nitrogen Dioxide (NO_2) is a highly variable atmosphere constituent, both in the stratosphere and troposphere. NO_2 is found in the atmosphere as a key ingredient in the photochemical formation of smog and acid rain, NO_2 is a poisonous gas that forms during combustion. The concentration of NO_2 may be high due to pollution. And NO_2 along with other NO_x reacts with other chemicals in the air to form both particulate matter and ozone. Both are also harmful when inhaled due to their effects on the respiratory system.

The method for determining the amount of NO_2 in solar radiation is usually expressed in terms of reduced pathlength, in centimeter units. The optical depth of NO_2 can be calculated using an equation (2.8), It depends on the amount of NO_2 and absorption coefficient of NO_2 (Gueymard, 1995).

$$\tau'_{n,\lambda} = -A_{n\lambda} NO_2 \tag{2.8}$$

where $\tau'_{n,\lambda}$ = the optical depth of NO_2 (-).

$A_{n\lambda}$ = absorption coefficient of NO_2 (cm^{-1}).

NO_2 = reduced pathlength of NO_2 (cm).

Spectral transmittance due to NO_2 was estimated by using the optical depth of NO_2, from equation (2.8). The equation is written as:

$$\tau_{n,\lambda} = \exp(-A_{n\lambda} NO_2 m_r) \tag{2.9}$$

where $\tau_{n,\lambda}$ = spectral transmittance caused by NO_2 (-).

m_r = relative air mass (-).

The spectral transmittance caused by NO_2 and ozone for different total path lengths are compared in Figure 7.

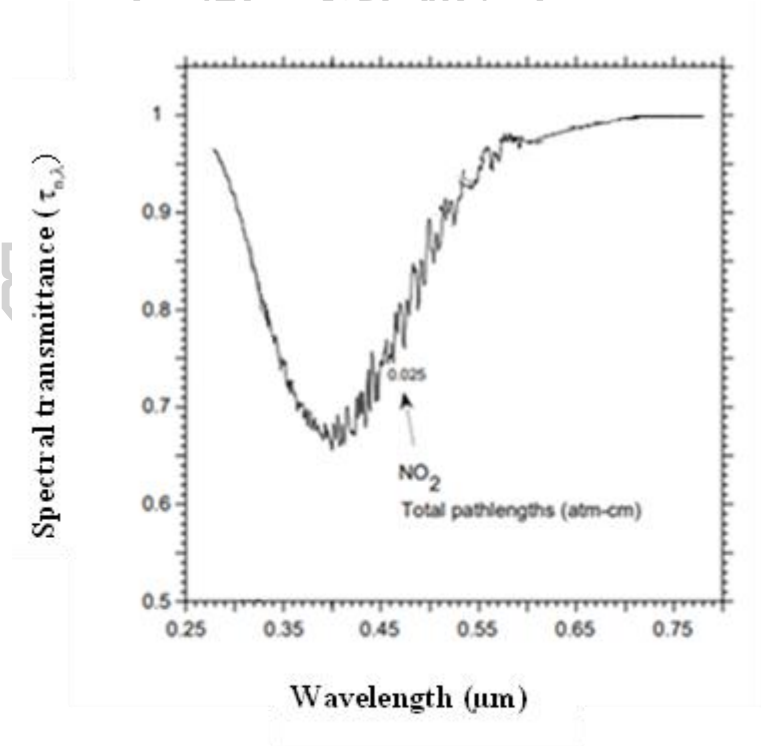

Figure 7 NO_2 transmittances for different total pathlengths (Adapted from Gueymard, 1995).

2.1.2.6 Absorption due to atmospheric mixed gases

Some atmospheric constituents are oxygen (O_2) and carbon dioxide (CO_2), with small amounts of others such as nitrous oxide (N_2O) and carbon monoxide (CO), known as a mixed gas. There are many types of such gases, therefore, the convenience of calculating transmittance due to mixed gases will be considered with only one coefficient. Spectral transmittance caused by mixed gases was calculated using an empirical equation proposed by Leckner (1978). The equation is written as:

$$\tau_{g,\lambda} = \exp[(-1.41 k_{g\lambda} m_a / (1+118.93 k_{g\lambda} m_a)^{0.45}] \qquad (2.10)$$

where $\tau_{g,\lambda}$ = spectral transmittance caused by mixed gases (-).

$k_{g\lambda}$ = extinction coefficient of gases (cm^{-1}).

m_a = air mass (-).

The spectral transmittance caused by mixed gases at each wavelength is shown in Figure 8. This clearly shows that the mixed gases are the most important absorber in the IR wavelength range about 2.8 µm (Iqbal, 1983).

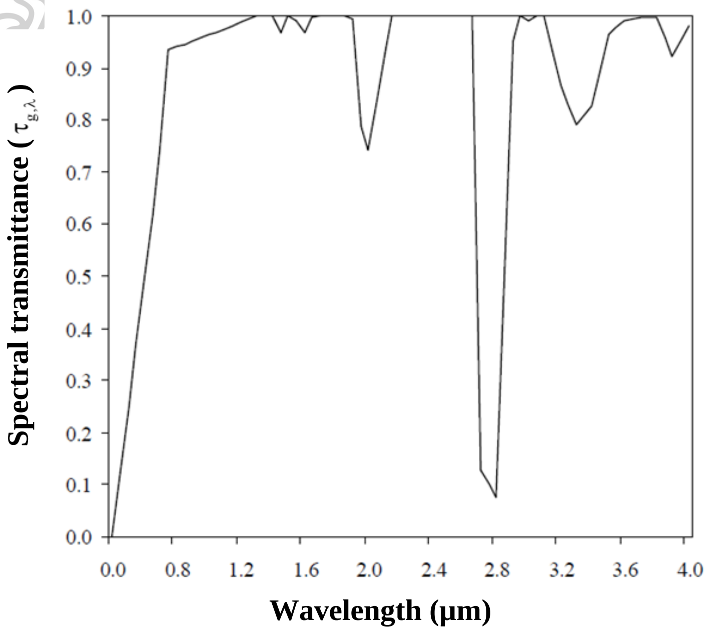

Figure 8 The spectral transmittance caused by mixed gases at each wavelength. (Adapted from Iqbal, 1983)

2.1.2.7 The effect of clouds on solar radiation

A cloud is a hydrometeor consisting of small particles of liquid water or ice, or of both, suspended in the atmosphere and above the earth's surface (Yang et al., 1998). Types of clouds according to height, are divided into 3 types: high cloud, Middle and low clouds generally consist of water vapor, but high clouds consist of ice crystals.

The effect of clouds on solar radiation is that clouds have a significant effect on reducing, the solar radiation reaching the surface from the atmosphere. Clouds reflect a portion of solar radiation outside the atmosphere and some toward the Earth's surface, in the form of diffuse radiation. Additionally, clouds are the most important absorbers in the IR wavelength range (Stephens et al., 1978), the absorption coefficient of clouds at each wavelength is shown in Figure 9.

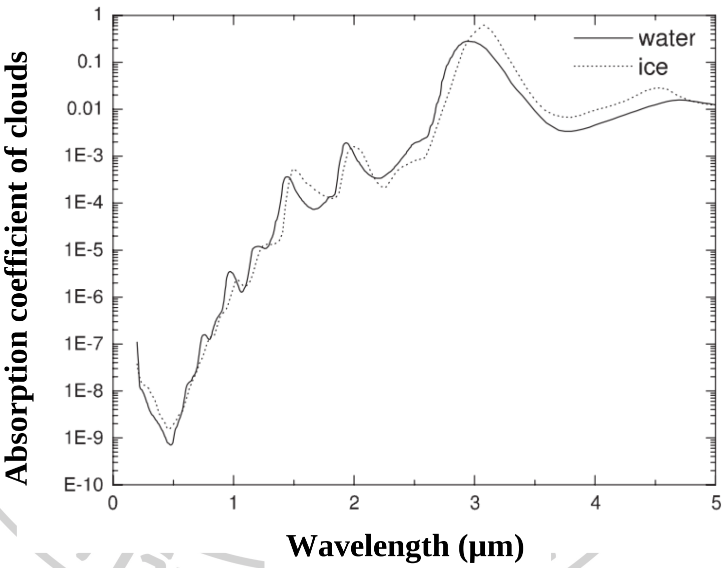

Figure 9 The absorption coefficient of clouds at each wavelength (Kokhanovsky & Zege, 2004).

2.2 Collection of ground-based spectral solar irradiance

The spectral solar irradiance reaching the earth's surface consists of two main components: direct spectral irradiance and diffuse spectral irradiance, the sum of direct spectral irradiance and diffuse spectral irradiance on a horizontal surface is global spectral irradiance. Solar spectral irradiance was measured every 1-minute interval using spectroradiometer. The position for the spectroradiometer is a location has a full hemispheric, without any obstructions such as buildings, trees, and mountain. Then connect to the computer for processing the data acquired by a spectroradiometer, it is employed to measure and analyze data. Workflow of spectroradiometer is depicted in Figure 10.

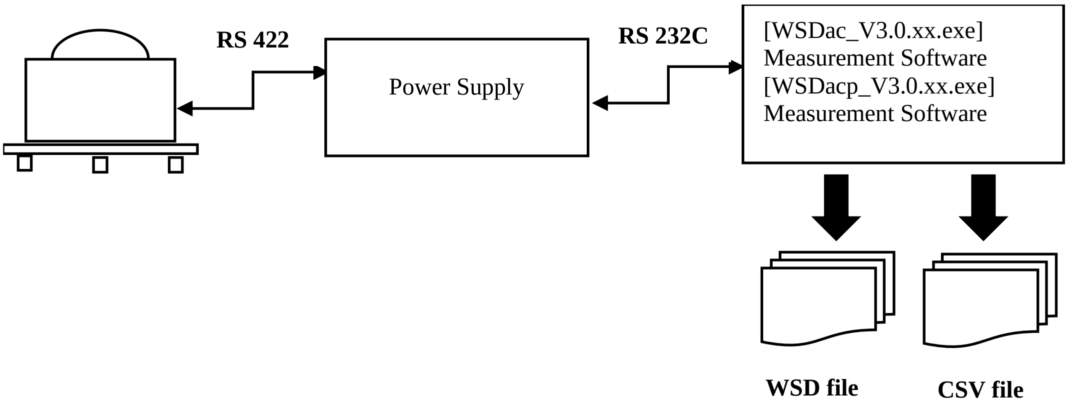

Figure 10 Workflow of spectroradiometer

A spectroradiometer (Figure 11) provides spectral range measurements from 0.35-0.95 μm. Spectroradiometers are accurately calibrated with traceability to the International Standards and issued with a calibration uncertainty budget. Example of spectral solar irradiance data obtained from spectroradiometer (EKO, ms-710 spectroradiometer) and example of spectrum of global irradiance is shown in Figure 12.

Figure 11 Spectroradiometer

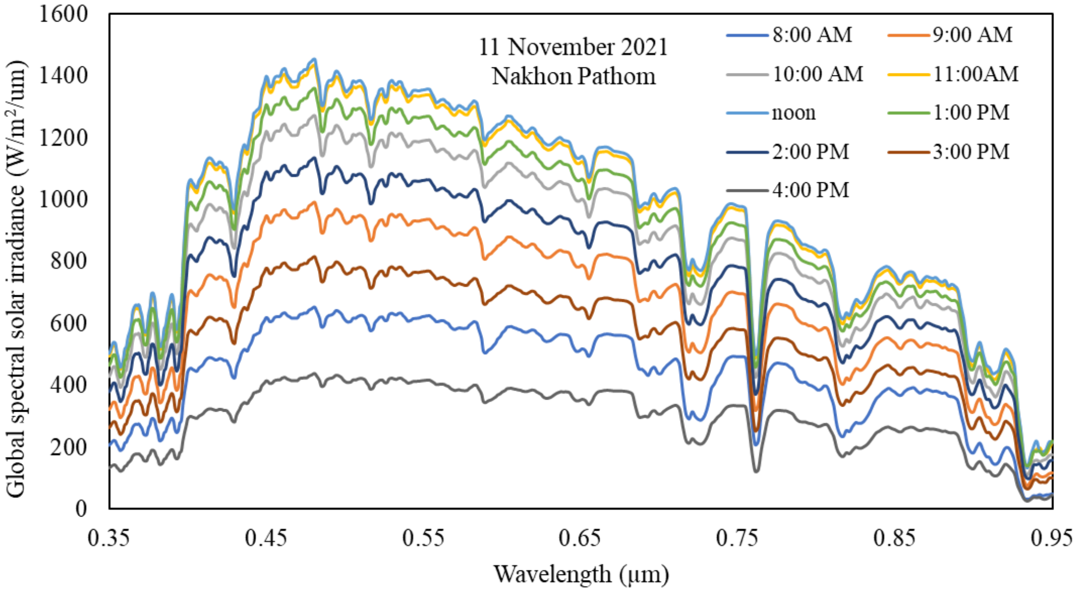

Figure 12 Examples of spectral solar data at Nakhon Pathom station.

2.2 Cloud Index (n) from Satellite Data

There are two types of meteorological satellites: polar orbiting satellites and geostationary satellites. The polar-orbiting satellites, in their north-south orbits, achieve higher resolution and accuracy because they are closer to the Earth's surface. Geostationary satellites are in orbit around 36,000 kilometers above the equator, orbit the Earth at the same rate as the Earth, and constantly focus on the same area. This enables the satellite to take a picture of the Earth, at the same location, every 15 minutes (Perez et al., 2013). Geostationary and polar-orbiting satellite orbits and operational field of views. The orbital of the geostationary and polar-orbiting satellites is shown in Figure 13. Example of the geostationary satellite data, Himawari-8 satellite data, is shown in Figure 14.

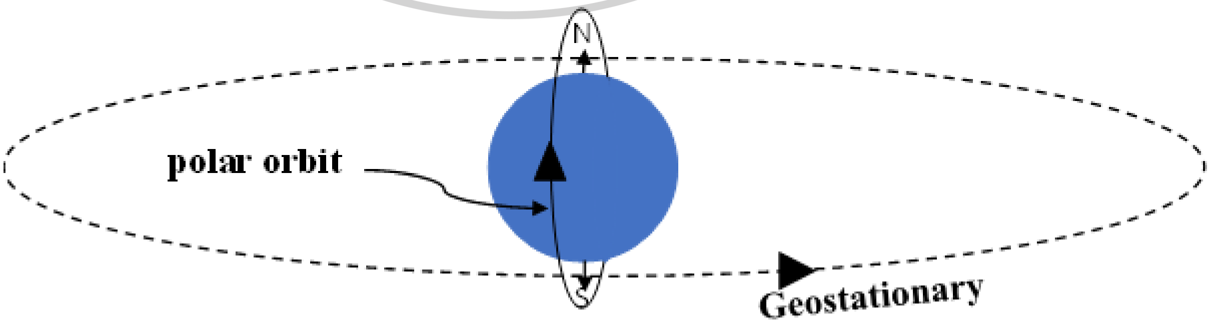

Figure 13 The orbital of the geostationary and polar-orbiting satellites

Figure 14 Example of Himawari-8 satellite data, on 27 February 2023 at 5:30 UTC. (From website: https://www.goes.noaa.gov/f_himawari-8.html)

Cloud index (n) can be obtained from meteorological satellite data (Cano et al., 1986). A conversion of the digital count obtained from satellite data to pseudo-reflectivity (ρ') was accomplished using a calibration table provided by the satellite agency. The values of ρ'' were then divided by cosine of local solar zenith angle and the earth-atmosphere reflectivity (ρ'_{EA}) were obtained. Minimum reflectivity (ρ'_{min}) obtained from the lowest satellite-derived reflectivity. On the other hand (ρ'_{max}) maximum reflectivity obtained from the highest satellite-derived reflectivity. Finally, values of ρ'_{EA} , ρ'_{min} , and ρ'_{max} obtained from satellite data were used to calculate cloud index (n) by using the formular proposed by Cano et al. (1986).

$$n = \frac{\rho'_{EA} - \rho'_{min}}{\rho'_{max} - \rho'_{min}} \tag{2.11}$$

where n = satellite derived-cloud index (-).

ρ'_{EA} = the earth-atmosphere reflectivity (-).

ρ'_{min} = minimum reflectivity (-).

ρ'_{max} = maximum reflectivity (-).

2.4 Literature reviews

Solar radiant energy received at the Earth's surface is of primary importance in a variety of fields. These fields include climate studies, atmospheric physics, solar thermal, remote sensing applications. The photovoltaic applications, solar cell spectral response can be obtained by testing and a specific cell will have a certain spectral response curve, so for the same solar cell, the output current changes will be mainly from the different spectrums. Spectral response of solar cells made of several different materials is depicted in Figure 15 (Dinpu et al., 2012). Nevertheless, spectral solar measurements are not available in many instances and areas, so models can only be used to fill this gap. In the early 1980s, numerous models appeared in the literature that simulated the real atmosphere (Jacovides et al., 2004).

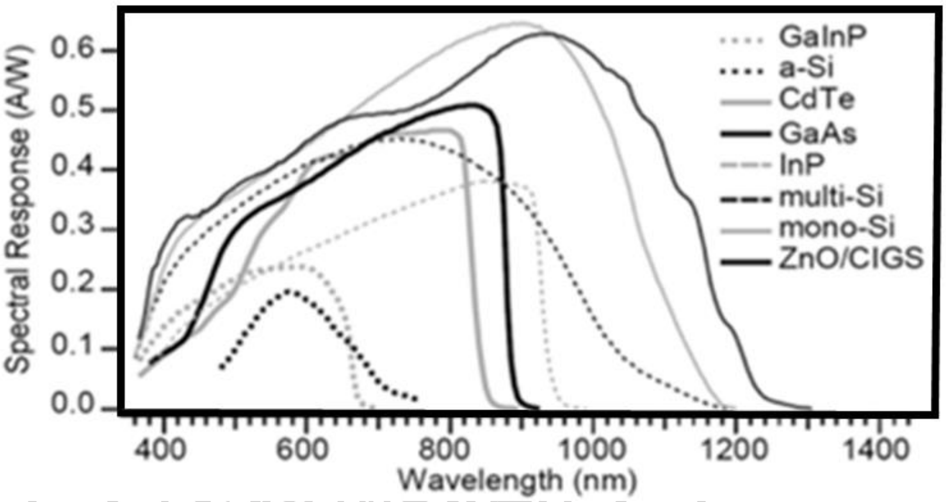

Figure 15 Spectral response of solar cells made from different materials (Adapted from Dingpu, 2016).

Brine & Iqbal (1983) proposed a simplified physical model used to calculate the spectral solar irradiance under clear sky conditions (Brine & Iqbal, 1983). The model is based on the parametric schemed previously developed by Leckner (1978) who used recent data to develop monochromatic transmission functions and calculated direct and diffuse spectral solar irradiance. This direct spectral solar irradiance model uses extraterrestrial solar spectral and explicit transmittances for Rayleigh scattering, ozone absorption, water vapor absorption, mixed gas absorption, and aerosol extinction, as written Equation 2.12. The diffuse spectral solar irradiance model Equation 2.13 is assumed to be composed of three parts: (1) Rayleigh-scattered diffuse irradiance; (2) aerosol-scattered diffuse irradiance; and (3) irradiance arising out of multiple reflections between the atmosphere and the ground, as an Equation 2.14 – 2.16. Finally, global spectral solar irradiance is sum of direct and diffuse spectral solar irradiance on horizontal surface (Equation 2.17).

$$\dot{I}_{n\lambda} = \dot{I}_{on\lambda}\tau_{R\lambda}\tau_{aer,\lambda}\tau_{w\lambda}\tau_{o\lambda}\tau_{g\lambda} \quad (2.12)$$

$$\dot{I}_{d\lambda} = \dot{I}_{dR\lambda} + \dot{I}_{d,aer,\lambda} + \dot{I}_{dm\lambda} \quad (2.13)$$

$$\dot{I}_{dR\lambda} = \dot{I}_{o\lambda}\cos\theta_z\tau_{w\lambda}\tau_{o\lambda}\tau_{g\lambda}\tau_{aer,\lambda}(1-\tau_{R\lambda})F_r \quad (2.14)$$

$$\dot{I}_{d,aer,\lambda} = \dot{I}_{no\lambda}\cos\theta_z\tau_{R\lambda}\tau_{w\lambda}\tau_{o\lambda}\tau_{g\lambda}(1-\tau_{aer,\lambda})\omega_0F_a \quad (2.15)$$

$$\dot{I}_{d,m,\lambda} = \left(\dot{I}_{dR\lambda} + \dot{I}_{d,aer,\lambda} + \dot{I}_{n\lambda}\cos\theta_z\right)\rho_{G\lambda}\rho_{a\lambda} / (1-\rho_{G\lambda}\rho_{a\lambda}) \quad (2.16)$$

$$\dot{I}_{g\lambda} = \dot{I}_{n\lambda}\cos\theta_z + \dot{I}_{d\lambda} \quad (2.17)$$

where $\dot{I}_{n\lambda}$ = direct spectral solar irradiance (W/m^2/μm).

$\dot{I}_{on\lambda}$ = extraterrestrial solar spectral irradiance (W/m^2/μm).

$\tau_{x\lambda}$ = transmittance functions due to atmospheric parameters (-).

$\dot{I}_{d\lambda}$ = diffuse spectral solar irradiance (W/m^2/μm).

$\dot{I}_{dR\lambda}$ = Rayleigh-scattered spectral solar irradiance (W/m^2/μm).

$\dot{I}_{d,aer,\lambda}$ = aerosol-scattered spectral solar irradiance (W/m^2/μm).

$\dot{I}_{dm\lambda}$ = spectral solar irradiance due to multiple reflections (W/m^2/μm).

θ_z = solar zenith angle (degree).

F_r = the Rayleigh forward-scattering ratio, generally taken as 0.5 (-).

ω_0 = the single scattering albedo (-).

F_a = the effective scattering ratio (-).

$\rho_{G\lambda}$ = the ground albedo (-).

$\rho_{a\lambda}$ = the monochromatic atmospheric albedo (-).

$\dot{I}_{g\lambda}$ = global spectral solar irradiance (W/m^2/μm).

Bird and Riordan (1986) proposed a simple model which can be used to calculate the direct and diffuse spectral solar irradiance under clear conditions. The SPCTRAL2 model proposed by Bird and Riordar (1986) is based on the parametric schemed previously developed by Leckner (1978) and Brine & Iqbal (1983). Bird and Riordan introduced some corrections and modifications to the previous simple model, including the addition of an earth-sun distance factor and some modifications of absorption coefficients (Bird, 1984). The model for calculating direct and diffuse spectral solar irradiance is shown in Equations 2.18-2.22. Global spectral solar irradiance is sum of direct and diffuse spectral solar irradiance on horizontal surface (Equation 2.23).

$$\dot{I}_{n\lambda} = \dot{I}_{on\lambda} E_0 \tau_{R\lambda} \tau_{aer,\lambda} \tau_{w\lambda} \tau_{o\lambda} \tau_{g\lambda} \tag{2.18}$$

$$\dot{I}_{d\lambda} = \dot{I}_{dR\lambda} + \dot{I}_{d,aer,\lambda} + \dot{I}_{dm\lambda} \tag{2.19}$$

$$\dot{I}_{dR\lambda} = \dot{I}_{o\lambda} E_0 \cos\theta_z \tau_{w\lambda} \tau_{o\lambda} \tau_{g\lambda} \tau_{aa,\lambda} (1 - \tau_{R\lambda}{}^{0.95}) 0.5 \tag{2.20}$$

$$\dot{I}_{d,aer,\lambda} = \dot{I}_{no\lambda} E_0 \cos\theta_z \tau_{w\lambda} \tau_{o\lambda} \tau_{g\lambda} \tau_{aa,\lambda} \tau_{R\lambda}{}^{1.5} (1 - \tau_{as,\lambda}) \omega_0 F_a \tag{2.21}$$

$$\dot{I}_{d,m,\lambda} = \left(\dot{I}_{dR\lambda} + \dot{I}_{d,aer,\lambda} + \dot{I}_{n\lambda} \cos\theta_z \right) \rho_{G\lambda} \rho_{a\lambda} / (1 - \rho_{G\lambda} \rho_{a\lambda}) \tag{2.22}$$

$$\dot{I}_{g\lambda} = \dot{I}_{n\lambda} \cos\theta_z + \dot{I}_{d\lambda} \tag{2.23}$$

where $\dot{I}_{n\lambda}$ = direct spectral solar irradiance (W/m^2/μm).

$\dot{I}_{on\lambda}$ = extraterrestrial solar spectral irradiance (W/m^2/μm).

E_0 = the correction factor for the earth-sun distance (-).

$\tau_{x\lambda}$ = transmittance functions due to atmospheric parameters (-).

$\dot{I}_{d\lambda}$ = diffuse spectral solar irradiance (W/m^2/μm).

$\dot{I}_{dR\lambda}$ = Rayleigh-scattered spectral solar irradiance (W/m^2/μm).

$\dot{I}_{d,aer,\lambda}$ = aerosol-scattered spectral solar irradiance (W/m^2/μm).

$\dot{I}_{dm\lambda}$ = spectral solar irradiance due to multiple reflections (W/m^2/μm).

θ_z = solar zenith angle (degree).

ω_0 = the single scattering albedo (-).

F_a = the effective scattering ratio (-).

$\rho_{G\lambda}$ = the ground albedo (-).

$\rho_{a\lambda}$ = the monochromatic atmospheric albedo (-).

$\dot{I}_{g\lambda}$ = global spectral solar irradiance (W/m^2/μm).

Gueymard (2001) developed a model called SMART2. This model can be used to calculate direct and diffuse spectral solar irradiance under clear conditions. The spectral solar irradiance is calculated from the spectral transmittance functions of the extinction processes in atmospheric as air molecules scattering, aerosols extinction, and mixed gas, water vapor, nitrogen dioxide, and ozone absorption. Nitrogen dioxide annihilation effects in the UV and VIS wavelength ranges were first proposed in the SMART model (Gueymard, 2001). The model also uses temperature and earth's surface as the main inputs. Temperature-dependent, pressure-dependent, and relative humidity attenuation coefficients have been developed for all these absorbed gases. The single scattering and asymmetry coefficients used in this model are provided as functions of wavelength and relative humidity. The model for calculating direct and diffuse spectral solar irradiance is shown in Equations (2.24-2.28). Global spectral solar irradiance is sum of direct and diffuse spectral solar irradiance on horizontal surface (Equation 2.29).

$$\dot{I}_{n\lambda} = \dot{I}_{on\lambda} E_0 \tau_{R\lambda} \tau_{aer,\lambda} \tau_{w\lambda} \tau_{o\lambda} \tau_{g\lambda} \tau_{n\lambda} \tag{2.24}$$

$$\dot{I}_{d\lambda} = \dot{I}_{dR\lambda} + \dot{I}_{d,aer,\lambda} + \dot{I}_{dm\lambda} \tag{2.25}$$

$$\dot{I}_{dR\lambda} = \dot{I}_{o\lambda} E_0 \cos\theta_z \tau_{w\lambda} \Gamma_{o\lambda} \tau_{g\lambda} \tau_{aa,\lambda} (1 - \tau_{R\lambda}{}^{0.9}) 0.5 \tag{2.26}$$

$$\dot{I}_{d,aer,\lambda} = \dot{I}_{no\lambda} E_0 \cos\theta_z \tau_{w\lambda} \Gamma_{o\lambda} \tau_{g\lambda} \tau_{aa,\lambda} \tau_{R\lambda} (1 - \tau_{as,\lambda}) \omega_0 F_a \tag{2.27}$$

$$\dot{I}_{d,m,\lambda} = \left(\dot{I}_{dR\lambda} + \dot{I}_{d,aer,\lambda} + \dot{I}_{n\lambda} \cos\theta_z\right) \rho_{G\lambda} \rho_{a\lambda} / (1 - \rho_{G\lambda} \rho_{a\lambda}) \tag{2.28}$$

$$\dot{I}_{g\lambda} = \dot{I}_{n\lambda} \cos\theta_z + \dot{I}_{d\lambda} \tag{2.29}$$

where $\dot{I}_{n\lambda}$ = direct spectral solar irradiance (W/m^2/μm).

$\dot{I}_{on\lambda}$ = extraterrestrial solar spectral iradiance (W/m^2/μm).

E_0 = the correction factor for the earth-sun distance (-).

$\tau_{x\lambda}$ = transmittance functions due to atmospheric parameters (-).

$\dot{I}_{d\lambda}$ = diffuse spectral solar irradiance (W/m^2/μm).

$\dot{I}_{dR\lambda}$ = Rayleigh-scattered spectral solar irradiance (W/m^2/μm).

$\dot{I}_{d,aer,\lambda}$ = aerosol-scattered spectral solar irradiance (W/m^2/μm).

$\dot{I}_{dm\lambda}$ = spectral solar irradiance due to multiple reflections (W/m^2/μm).

$\Gamma_{o\lambda}$ = ozone diffuse transmittance for downward scattering. (-)

θ_z = solar zenith angle (degree).

ω_0 = the single scattering albedo (-).

F_a = the effective scattering ratio (-).

$\rho_{G\lambda}$ = the ground albedo (-).

$\rho_{a\lambda}$ = the monochromatic atmospheric albedo (-).

$\dot{I}_{g\lambda}$ = global spectral solar irradiance ($W/m^2/\mu m$).

Jacovides et al. (2003) used the SPCTRAL2 parametric model providing estimates of spectral solar irradiances over both the complete solar spectrum (300 1100 nm) and two discrete spectral bands, ultraviolet (UV) and visible (VIS), under clear sky conditions. Algorithm predictions are compared against direct-beam solar spectra, obtained during a joint research experiment in the Athens basin, considering the impacts of different aerosol models included in the parametric scheme. Both MBD and RMSD indices increase with decreasing aerosol optical depth at 500 nm. The results present that the models behavior was explained by considering Angstrom's exponent values used by each model.

Torres-Ramírez et al. (2015) proposed a new spectral irradiance distribution estimation method based on artificial neural network techniques (ANN) (Torres-Ramírez et al., 2015). ANN models were developed for modeling, trained, and tested to model the spectral distributions between wavelengths ranging from 350 to 1050 nm. Only commonly available input data such as geographical information regarding the location-specific date and time together with horizontal global irradiance and ambient temperature are required. The best generalization results were obtained using two hidden layers with eighteen hidden neurons in each hidden layer. These models used a hyperbolic tangent sigmoid activation function and the Levenberg Marquardt learning algorithm. From the result the ANN model fits less well the shape of the spectral distribution for low in-plane global irradiation months. The best performance of this model has reached for summer-sunny weather conditions-where the collected irradiation accounts for 63.7% of the annual collected in-plane global irradiation.

Koussa et al. (2015) investigated models based on several monochromatic transmission coefficients related to the absorption and diffusion of solar radiation by the main constituents of the atmosphere (Koussa et al., 2015). These models allow evaluation of the spectral distribution of different components of solar radiation, namely normal direct, horizontal diffuse, and inclined diffuse and inclined global solar irradiance, under clear sky conditions. The geographical coordinates of the site and the monochromatic distribution of the extraterrestrial irradiance are used as input data. From three-year data measurement records made in the Bouzareah site (temperate climate), thirty-eight days characterized by a clear sky state have been selected from over different months of the year and the corresponding main meteorological parameters were used as input parameters. The results present that, the different solar radiation attenuation phenomena are highly dependent on the climate of the considered site and the considered season. Although the total diffuse solar irradiance follows a seasonal evolution, it is found that the part of the diffuse solar irradiance depends on the main constituents of the atmosphere as the molecular, aerosol, and multi-reflection scattering phenomena constitutes.

Nagaoka et al, (2021) approach is the development of a spectrum model that can be applied to all-climate and computed the performance varies according to the sun's orientation and incident angle (Nagaoka et al., 2021). The global solar spectrum was calculated using Equations (2.30). They take as known that the solar spectrum sunlight reaching a building surface is a linear combination of the clear sky spectrum and overcast skies spectrum. The correction factor of weather defined by the direct normal irradiance and integration of direct spectral under clear sky conditions, in 0.3-4.0 μm, this must be greater than zero to avoid division by zero. Finally, this model is used to estimate the performance of wall-mounted photovoltaics (PV) for building applications and has great potential for Zero Energy Building (ZEB).

$$\dot{I}_{\lambda} = f\dot{I}_{1\lambda} + (1-f)\dot{I}_{2\lambda} \tag{2.30}$$

where

$\dot{I}_{\lambda}$ global spectral solar irradiance covering all weather conditions ($W/m^2/\mu m$).

$\dot{I}_{1\lambda}$ = global spectral solar irradiance under clear sky conditions obtained from Bird's spectrum model ($W/m^2/\mu m$).

$\dot{I}_{2\lambda}$ = global spectral solar irradiance from a spectrum model that assumes full cloud cover ($W/m^2/\mu m$).

f = the correction factor of weather obtained from equation 2.33 (-).

$$f = \frac{DNI}{\int_{0.3\mu m}^{4.0\mu m} \dot{I}_{d\lambda} d\lambda}, (\dot{I}_{d\lambda} > 0) \tag{2.33}$$

where DNI = the direct normal irradiance (W/m^2).

$\dot{I}_{d\lambda}$ = direct spectral under clear sky conditions ($W/m^2/\mu m$).

From the literature review, the previously proposed model is complex because it contains many unknown variables and the calculation of the spectral solar irradiance can be limited for the location where the spectral solar irradiance data is not available if applied to other locations, resulting in high discrepancies. Therefore, it is necessary to create a more accurate empirical model for calculating the global solar spectrum in

Thailand, for the case of all-sky conditions. The details of the study are presented in the next chapters.

Chapter 3

Methodology, result, and discussion[1]

3.1 Methodology

The methodology used in this thesis is composed of measurement of various parameters of the model, formulation of the model, determination of model coefficients and model validation. This methodology is similar to that of the development of spectrum model for Nakhon Pathom, presented in appendix 2.

3.1.1 Measurement of various parameters

Various parameters were measured. The details of the measurement are as follows.

3.1.1.1 Measurement of solar spectrum

Global spectral solar irradiance was collected every 1-minute interval using EKO ms-710, 711 spectroradiometers. The MS-711 is a newer version than the MS-710 but these spectroradiometers use silicon detectors (Si) and have the same specifications. Spectroradiometers installed at Chiang Mai (18. 77˚ N, 98. 97˚ E) in the North, Ubon Ratchathani (15. 25˚ N, 104. 87˚ E) in the Northeast, Nakhon Pathom (13. 82˚ N, 100. 04˚ E) in the Center, and Songkhla (7. 18˚ N, 100.60˚ E) in the South. The positions and pictorial view of instruments installed and used in this study are shown in Figure 16.

The spectroradiometers are regularly calibrated by EKO, the manufacturer. The spectroradiometer is calibrated against a NIST (National Institute of Standards and Technology) traceable tungsten-halogen OL-FEL standard lamp at a distance of 50 cm. The standard lamp has a known spectrum, and the absolute irradiance is calibrated at several wavelengths. By measuring the spectroradiometer's detector responsivity in counts as a function of the irradiance at corresponding wavelengths, the sensitivity of each photodiode array pixel is converted into absolute units ($W/m^2/\mu m$). The calibration function is determined by averaging 10 measurements, measured separately for several different wavelength intervals each with a fixed exposure time. This is to use optimal output characteristics of the detector. Finally, the calibration function is uploaded to the spectroradiometer firmware for automatic conversion of the measured count into absolute units. The detail of calibration procedure is presented as follows:

[1] This part of the thesis was submitted to published in International Journal of Green Energy. The submitted manuscript was entitled “A model for computing spectral global solar irradiance under all-sky conditions in Thailand”.

- Wavelength calibration

1. Measuring Mercury Argon Lamp with MS-710, 711

2. Calculate the wavelength coefficient (the following approximation Equation (3.1)) from the relationship between the emission line wavelength of the mercury-argon lamp and the pixel number of the measurement data.

$$\lambda(n) = (C_5 * (n+1)^5) + (C_4 * (n+1)^4) + (C_3 * (n+1)^3) + (C_2 * (n+1)^2) + (C_1 * (n+1)) + C_0 \quad (3.1)$$

where λ = Wavelength (nm)

n = Pixel number (0 to 2047)

C_0, C_1, C_2, C_3, C_4, and C_5 = wavelength coefficient

3. Check that the difference between the emission line wavelength of the mercury-argon lamp and the wavelength calculated from the wavelength coefficient is within ±0.2 nm.

- Irradiance calibration

1. Measure NIST-compliant standard halogen lamps with MS-710, 711.

2. Calculate the sensitivity constant (counts/W/m^2/µm) from the spectral irradiance (W/m^2/µm) come with the standard halogen lamp and the measurement data (counts).

3. Re-measure the standard halogen lamp with MS- 710, 711 to which the sensitivity constant is applied and confirm that the measurement data (W/m^2/µm) is within the calibration uncertainty.

4. Spectral irradiance is expressed by the following Equation (3.2).

$$\dot{I}(\lambda n) = Cal(\lambda n) \times D(\lambda n) / T \quad (3.2)$$

where $\dot{I}(\lambda n)$ = Spectral irradiance (W/m^2/µm)

n = Pixel number (0 to 2047)

$Cal(\lambda n)$ = sensitivity constant (counts/W/m^2/µm)

$D(\lambda n)$ = measured data (counts)

T = Exposure time (seconds)

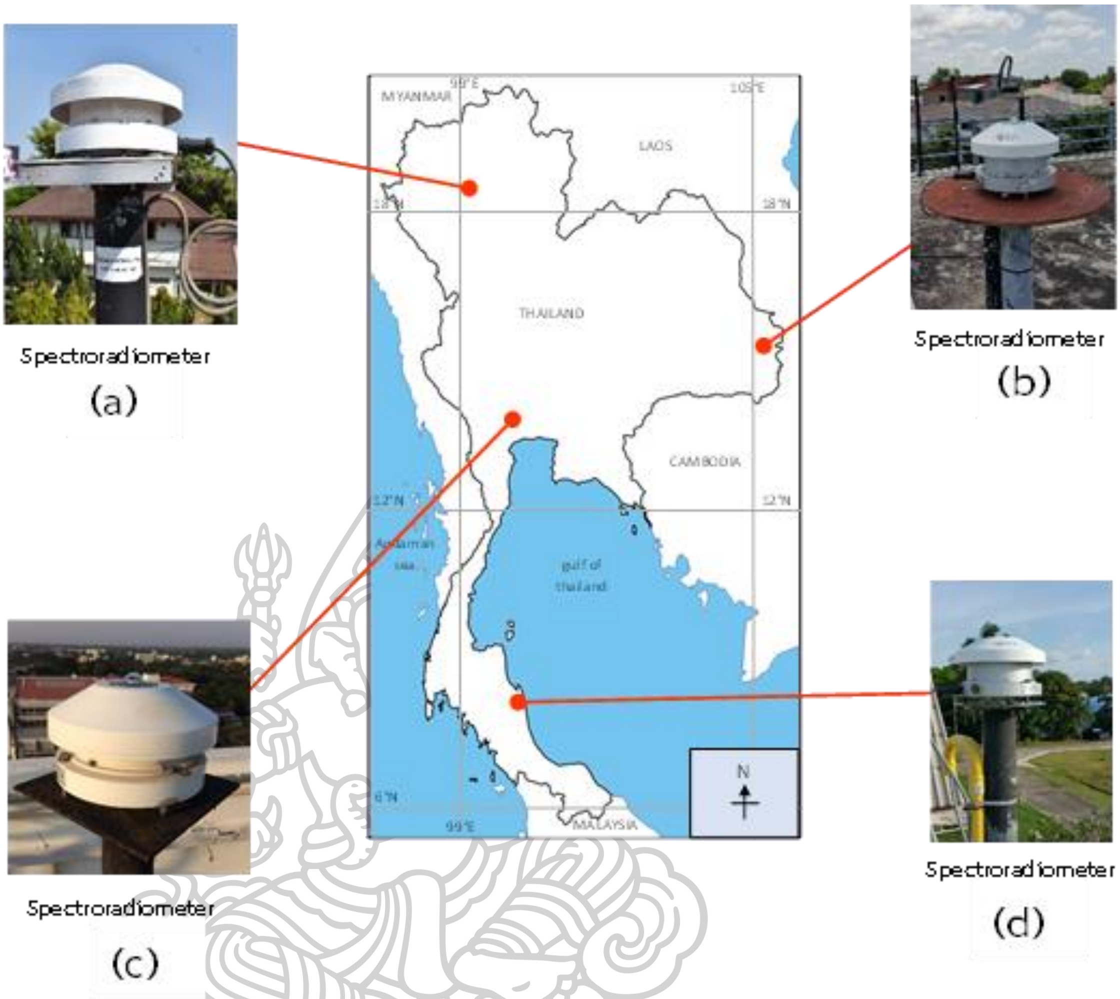

Figure 16 Spectroradiometers and locations of the measuring stations: (a) Chiang Mai station, (b) Ubon Ratchathani station, (c) Nakhon Pathom station and (d) Songkhla station.

The spectroradiometer waveband extends from 0.35 to 0.95 µm. The resolution of the spectrum is 0.001 µm. These instruments were programmed to measure the spectral solar irradiance every 1-minute interval from 8 A.M. – 4 P.M. The measurement data display window of WSDacV3.0.exe program shows the graph (Figure 17). This graph is updated for each measurement.

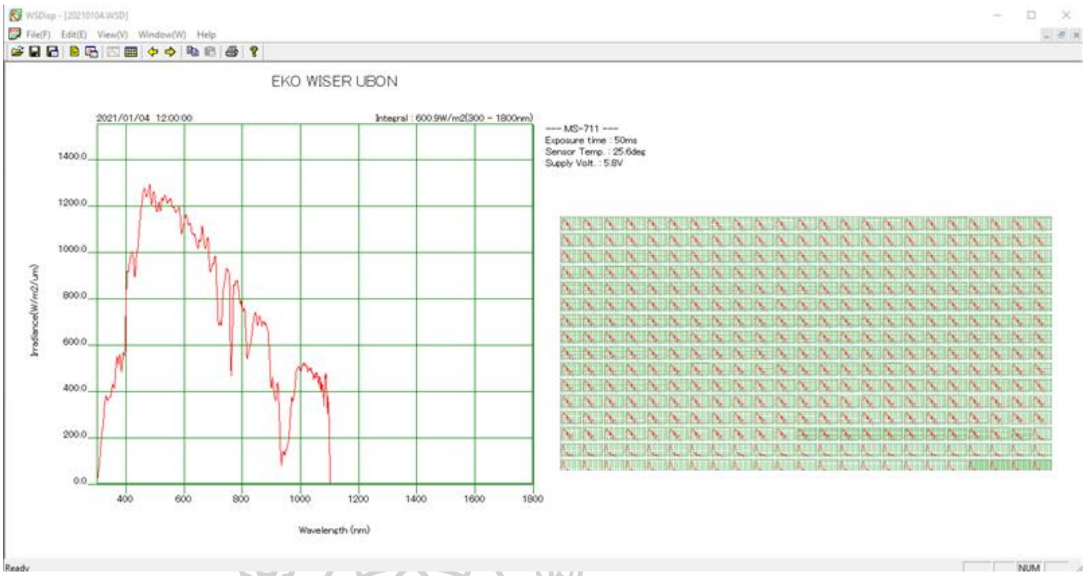

Figure 17 Measurement data display window of WSDacV3.0.exe program.

The 1-minute data collected from the instrument were averaged over 1-hour period (Figure 18-21). The hourly values of spectral solar irradiance from January 2017 to December 2020 were employed for creating the model and the data from January to December 2021 were used for model validation.

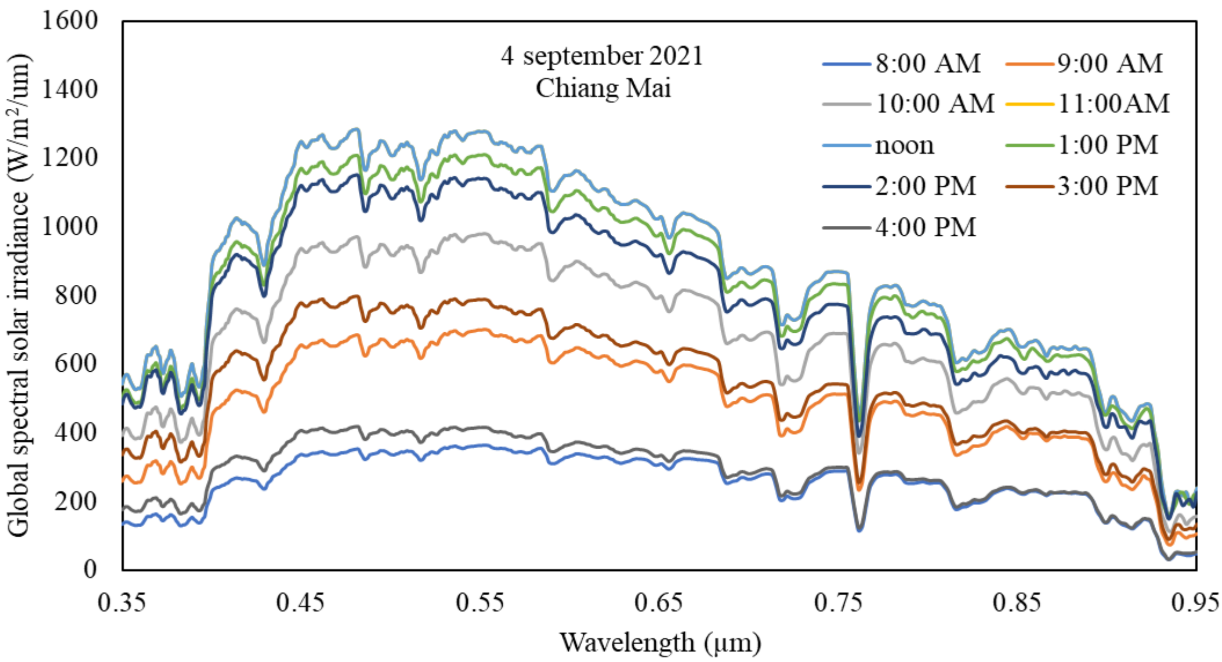

Figure 18 Example of the hourly values of global spectral solar irradiance on 4 September 2021 from Chiang Mai station

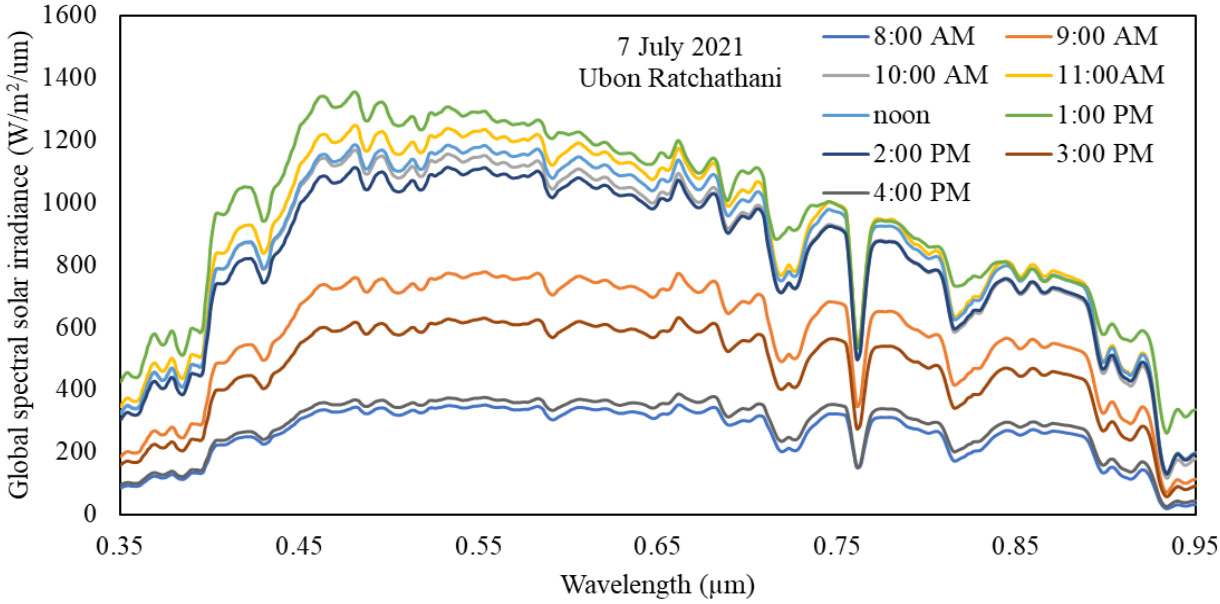

Figure 19 Example of the hourly values of global spectral solar irradiance on 7 July 2021 from Ubon Ratchathani station

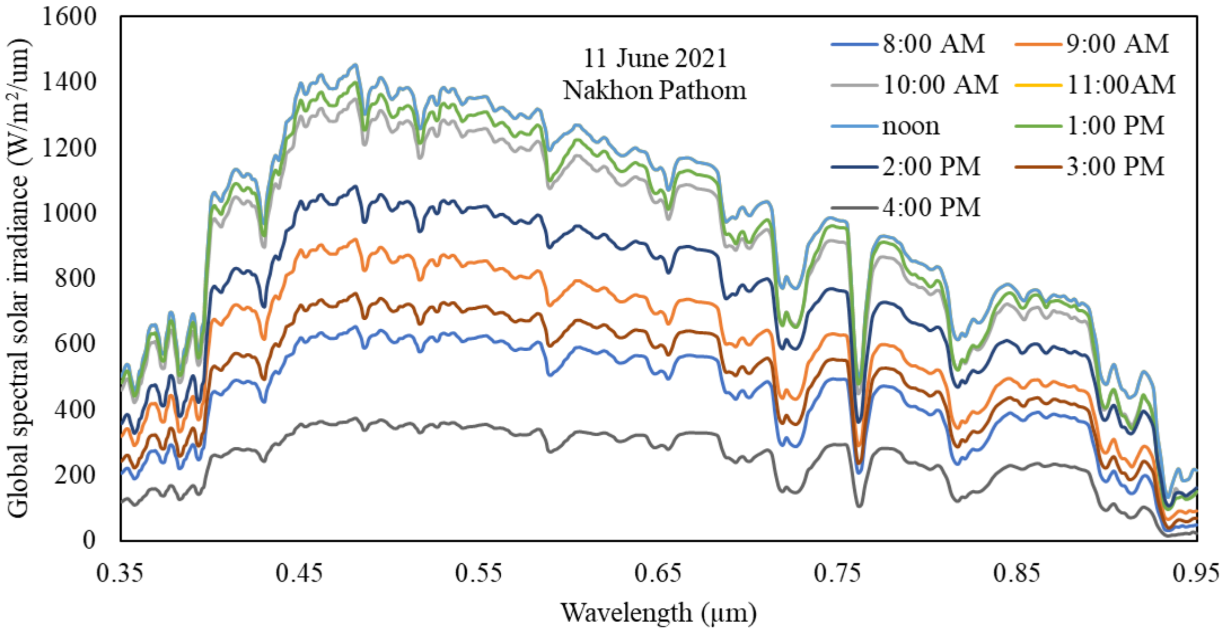

Figure 20 Example of the hourly values of global spectral solar irradiance on 11 June 2021 from Nakhon Pathom station

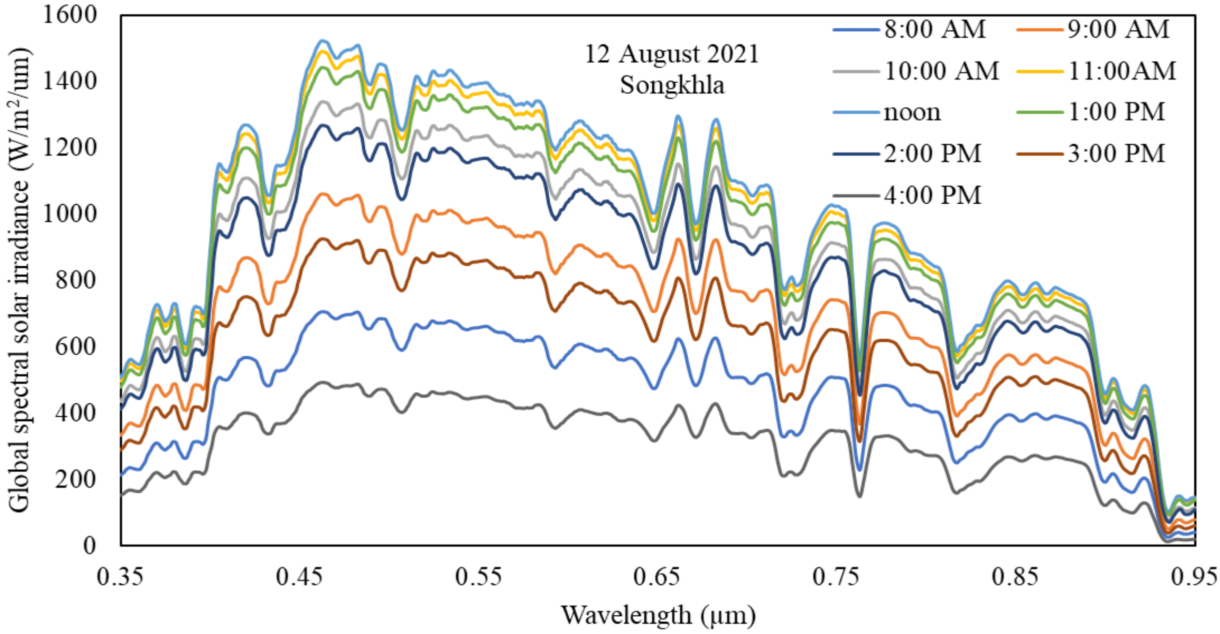

Figure 21 Example of the hourly values of global spectral solar irradiance on 12 August 2021 from Songkhla station

3.1.1.2 Measurements of the optical properties of aerosol

To create the spectral model, it is necessary to have data of aerosols optical depth (AOD). The data were obtained from an AERONET sunphotometer installed at the same station (Figure 22). The data from the sunphotometers were sent via the INTERNET to the AERONET headquarter in USA, and optical properties of aerosol and quantities of other atmospheric constituents were posted on the AERONET website. The sunphotometers are regularly calibrated by AERONET. In this study, Ångström turbidity coefficient at 340-1020 nm, Ångström wavelength exponent at 340-1020 nm, and data on aerosol optical depth (AOD) at 340, 380, 440, 500, 675, 870, and 1020 nm information were downloaded from the AERONET website.

The AOD for every wavelength from 350 to 950 nm was estimated by using Ångström turbidity coefficient (β), and Ångström wavelength exponent (α) obtained from the AERONET website (Equation 3.3).

$$AOD_{\lambda} = \beta\lambda^{-\alpha} \tag{3.3}$$

where AOD_{λ} = aerosol optical depth (-).

β = Ångström turbidity coefficient (-).

α = Ångström wavelength exponent (-).

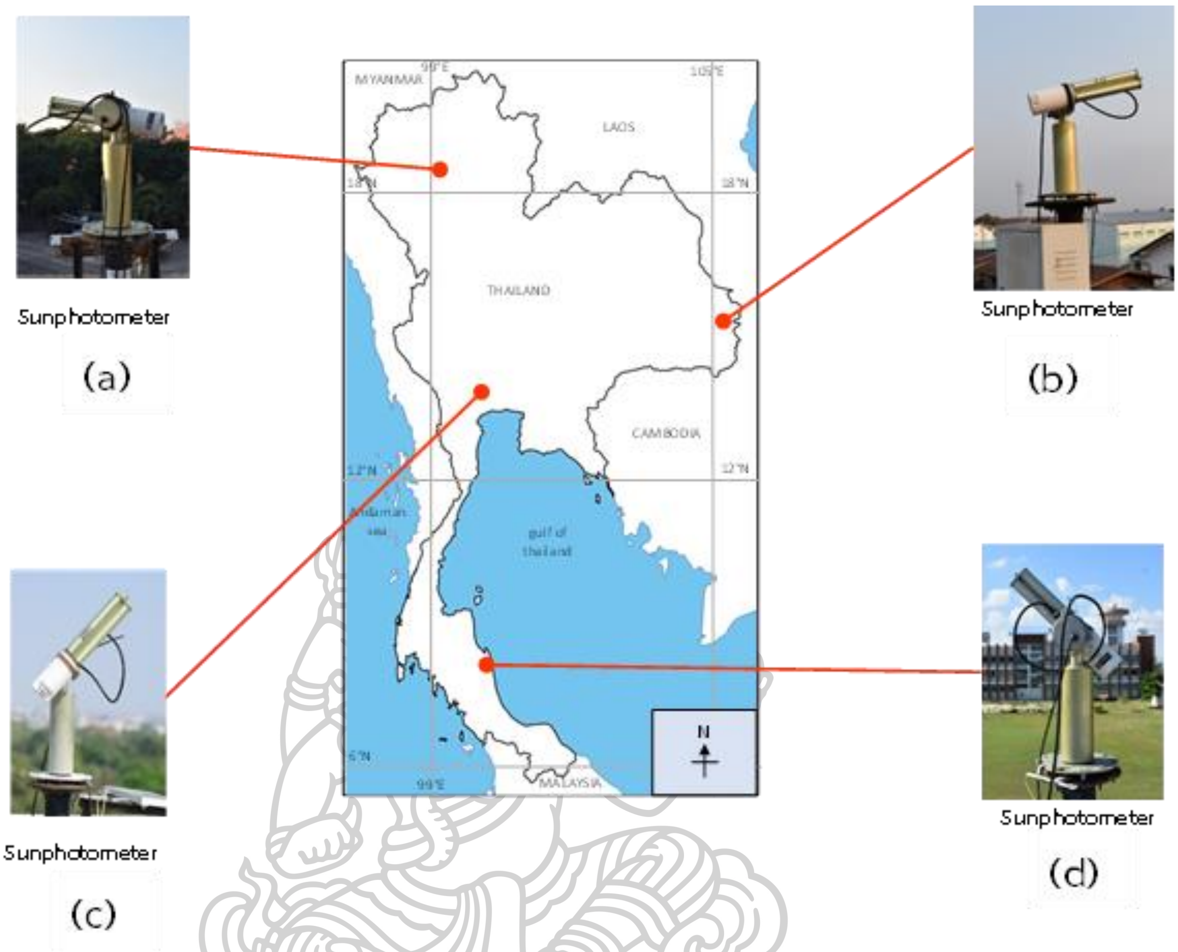

Figure 22 Sunphotometers and locations of the measuring stations: (a) Chiang Mai station, (b) Ubon Ratchathani station, (c) Nakhon Pathom station and (d) Songkhla station.

AOD data set was averaged over 1 hour period and subsequently used for developing and testing the model. The hourly values of AOD are separated into two groups. The first group (January, 2017 – December, 2020) was used for modeling while the second group (January – December, 2021) was employed for model validation. Example of the variation of hourly AOD at each wavelength of Chiang Mai, Ubon Ratchathani, Nakhon Pathom and Songkhla stations are presented in Figure 23-26.

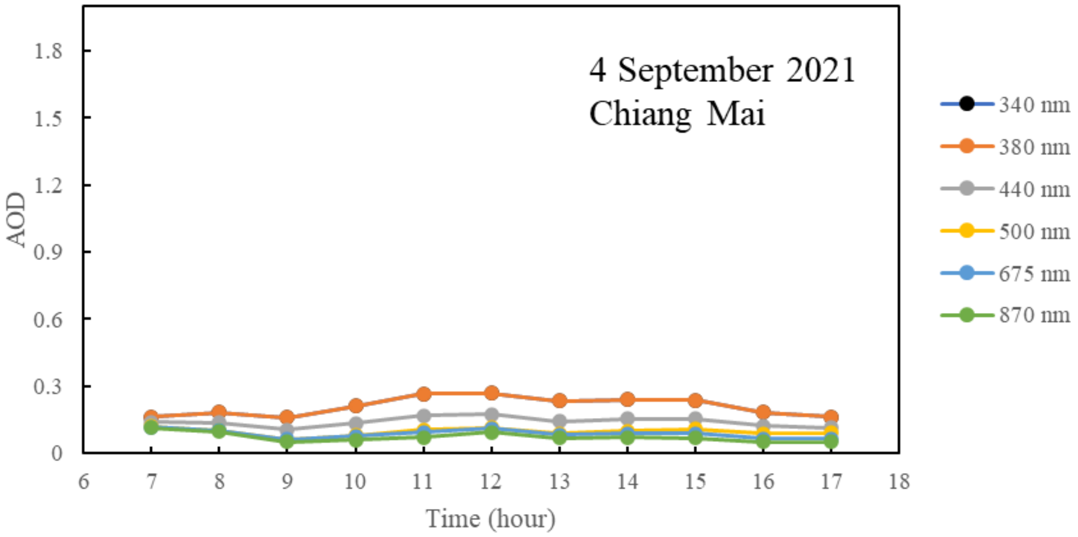

Figure 23 Examples of the variation of hourly AOD at 340, 380, 440, 500, 675, and 870 nm of Chiang Mai station.

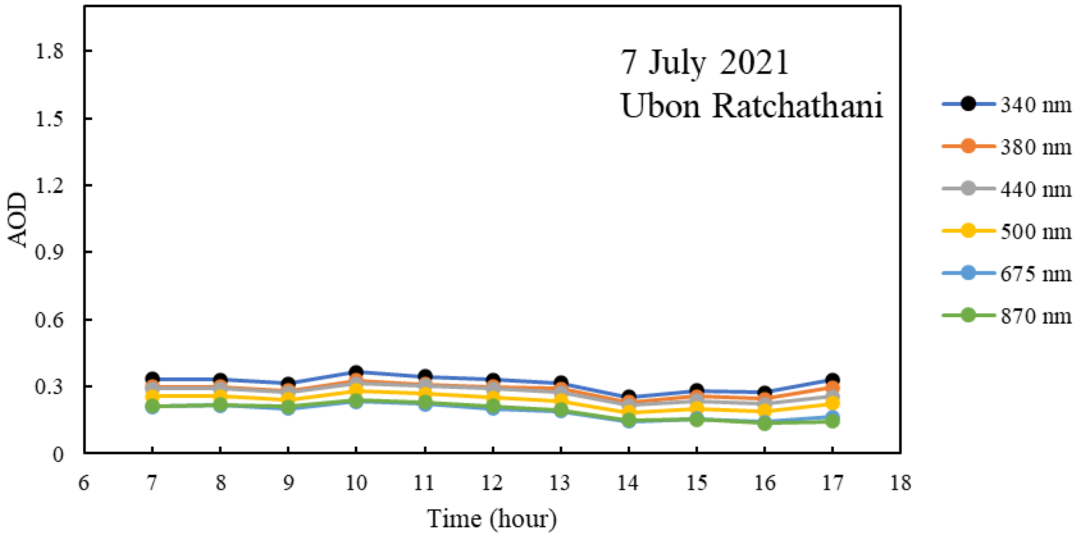

Figure 24 Examples of the variation of hourly AOD at 340, 380, 440, 500, 675, and 870 nm of Ubon Ratchathani station.

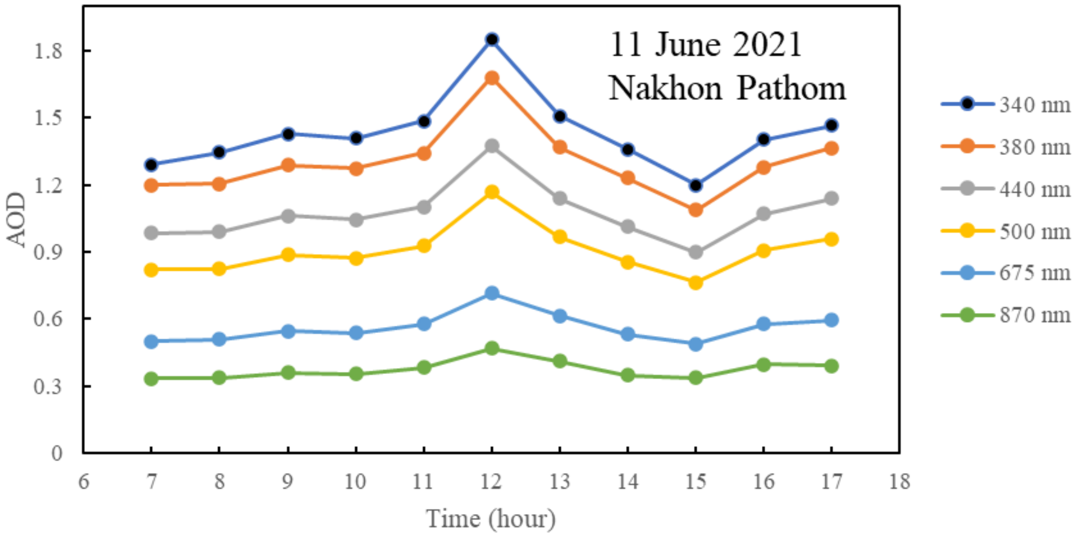

Figure 25 Examples of the variation of hourly AOD at 340, 380, 440, 500, 675, and 870 nm of Nakhon Pathom station.

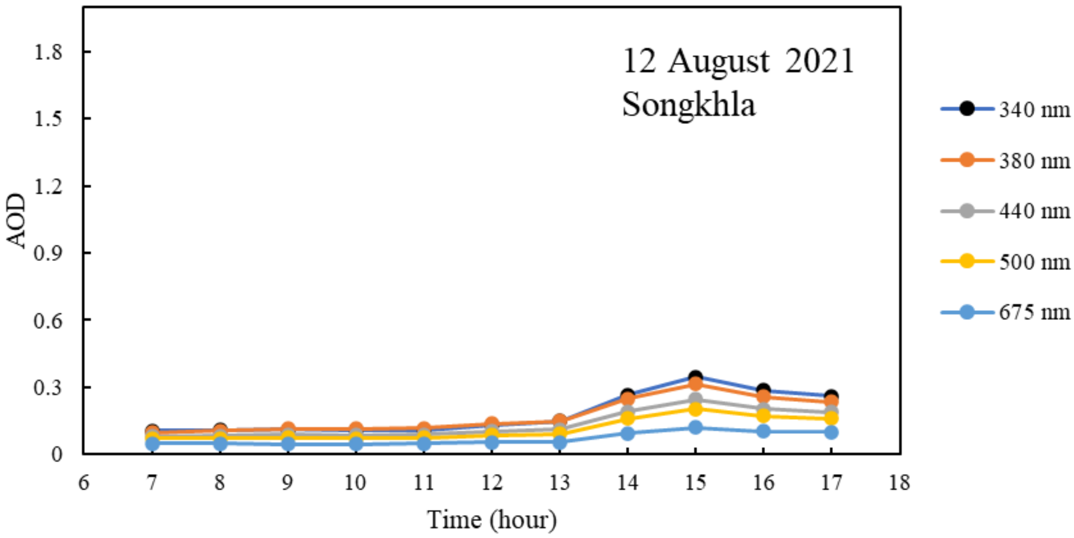

Figure 26 Examples of the variation of hourly AOD at 340, 380, 440, 500, 675, and 870 nm of Songkhla station.

From Figure 23-26, it was found that the AOD is highest at 340 nm and decreases gradually with increasing wavelength. AOD values tend to be higher during the day.

3.1.1.3 Measurements of precipitable water (W), amount of ozone (O_3) and nitrogen dioxide (NO_2)

Precipitable water (W), ozone amount (O_3) and nitrogen dioxide amount (NO_2) were measured by AERONET and they were posed at the website https://aeronet.gsfc.nasa.gov/. They were downloaded from this website and they were separated into two groups. The first group (January, 2017 – December, 2020) was used for modeling while the second group (January – December, 2021) was employed for model validation. The variation of hourly W, O_3 and NO_2 for Chiang Mai, Ubon Ratchathani, Nakhon Pathom and Songkhla station are presented in Figure 27-30.

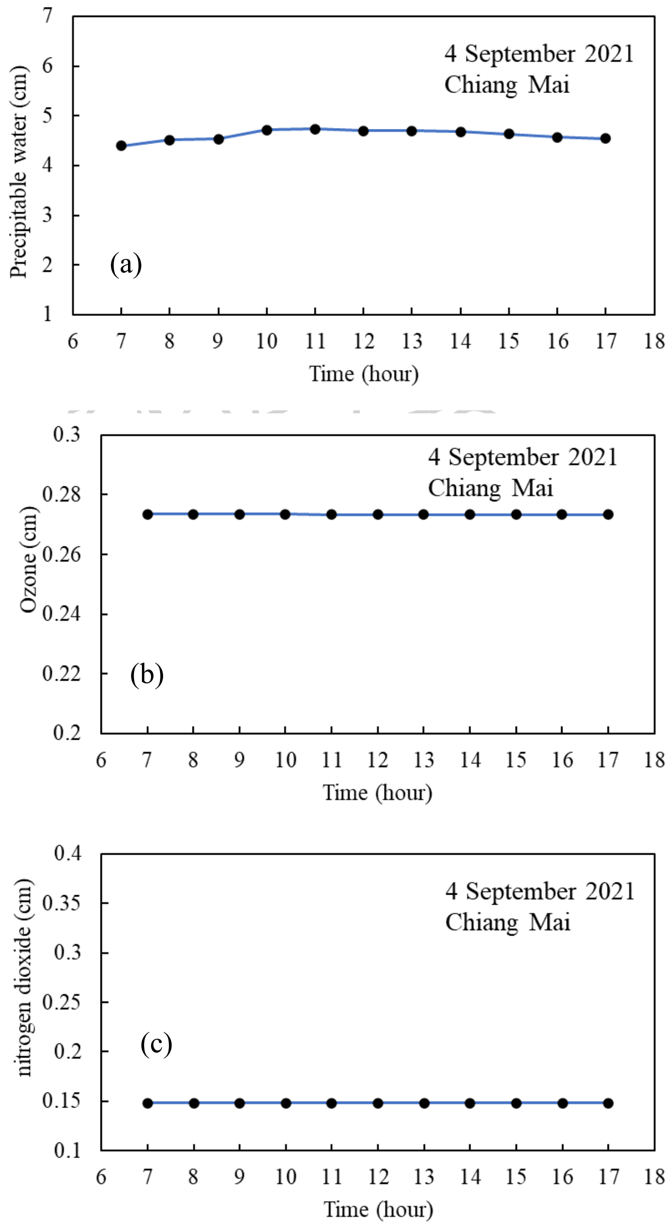

Figure 27 Examples of the variation of hourly (a) precipitable water (W), (b) ozone amount (O_3) and (c) nitrogen dioxide amount (NO_2) of Chiang Mai station

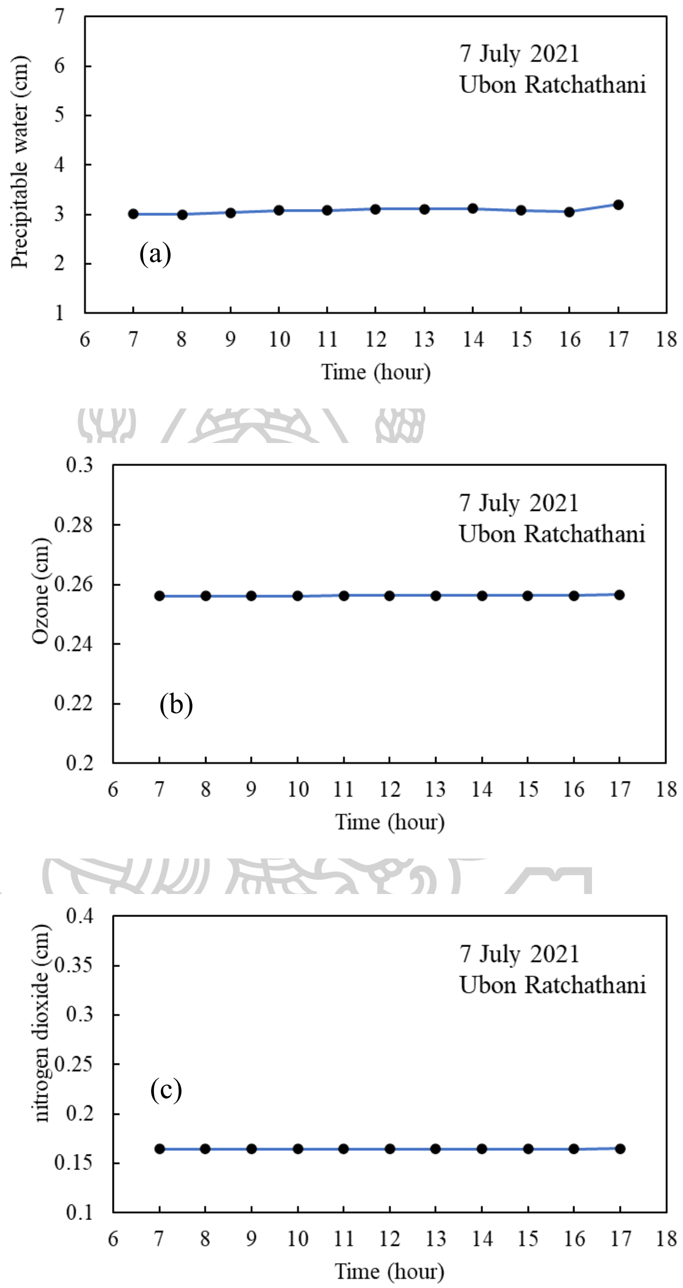

Figure 28 Examples of the variation of hourly (a) precipitable water (W), (b) ozone amount (O_3) and (c) nitrogen dioxide amount (NO_2) of Ubon Ratchathani station.

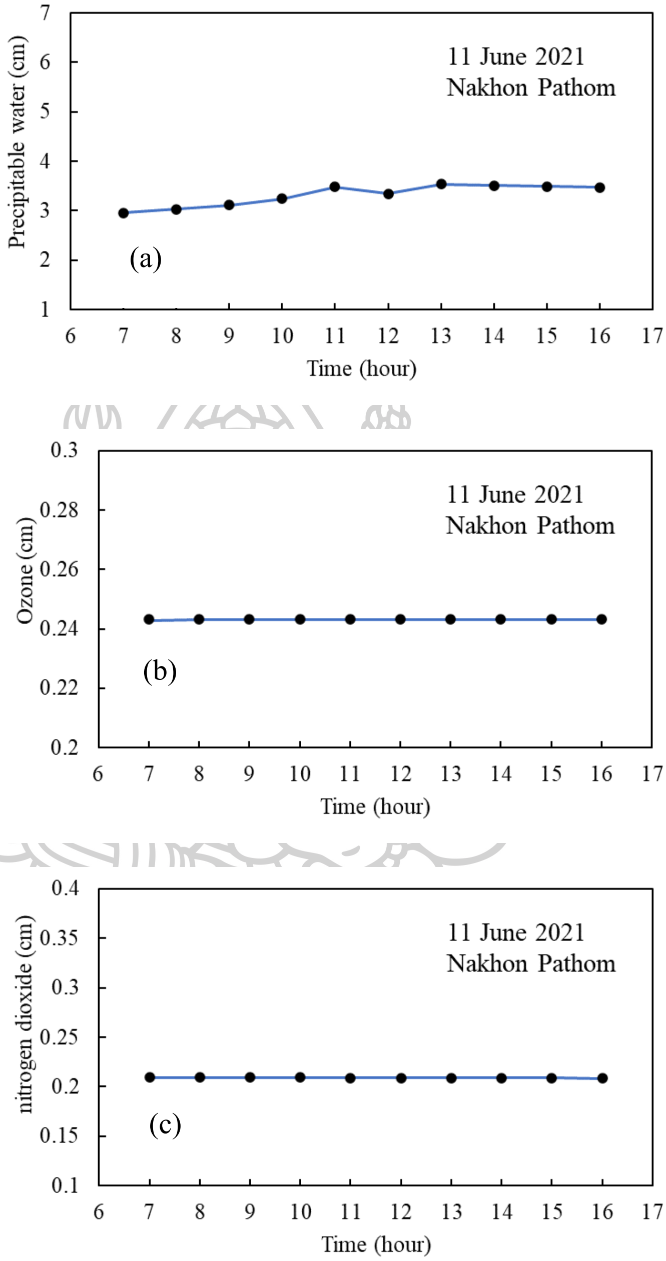

Figure 29 Examples of the variation of hourly (a) precipitable water (W), (b) ozone amount (O_3) and (c) nitrogen dioxide amount (NO_2) of Nakhon Pathom station.

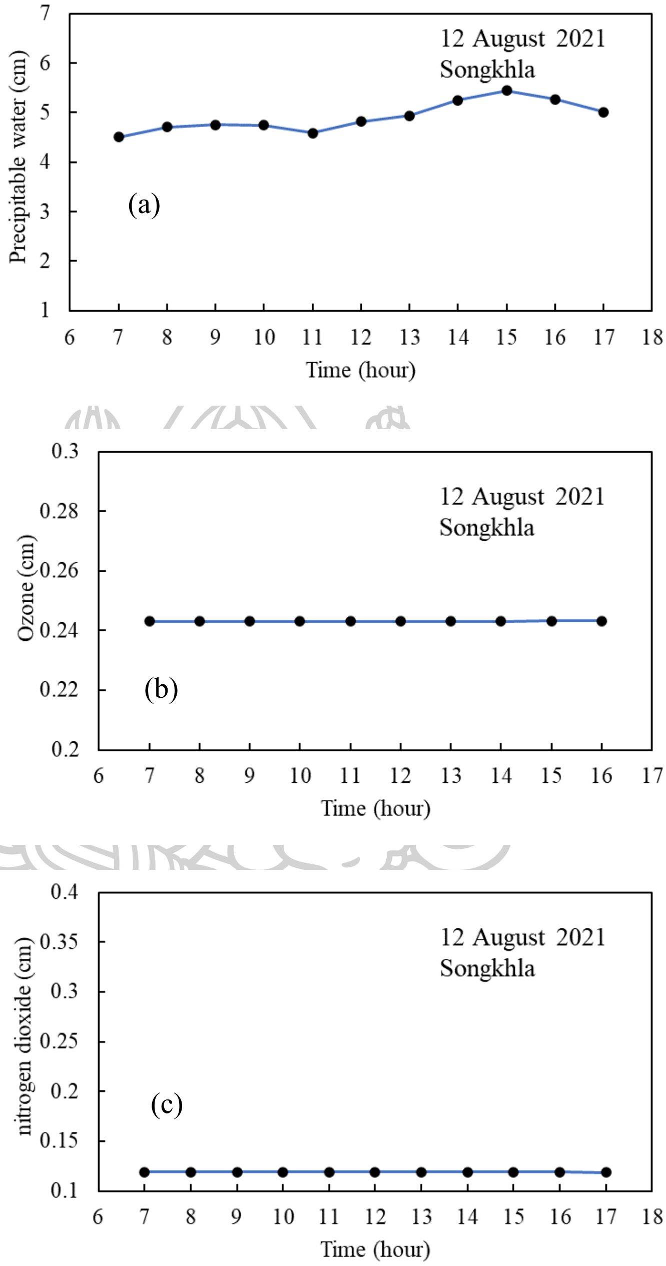

Figure 30 Examples of the variation of hourly (a) precipitable water (W), (b) ozone amount (O_3) and (c) nitrogen dioxide amount (NO_2) of Songkhla station.

From Figure 27-30, it indicates that the variation of precipitable water (W) in all stations is high between noon and evening, which is a result of air temperature. And the variation of ozone (O_3) and nitro dioxide (NO_2) is relatively constant.

3.1.1.4 Satellite derived-cloud index

The satellite data used in this work are 8-bit digital data from a visible channel of geostationary meteorological satellites, Himawari-8 satellite. The visible images taken from Himawari-8 satellite (Figure 31) were used to provide information on clouds over the Chiang Mai, Ubon Ratchathani, Nakhon Pathom, and Songkhla stations. The total period of the data is 5 years. The first group (January, 2017 – December, 2020) was used for modeling while the second group (January – December, 2021) was used for model validation. The raw visible images were transformed to the rectified images using the process described in Janjai et al. (2005).

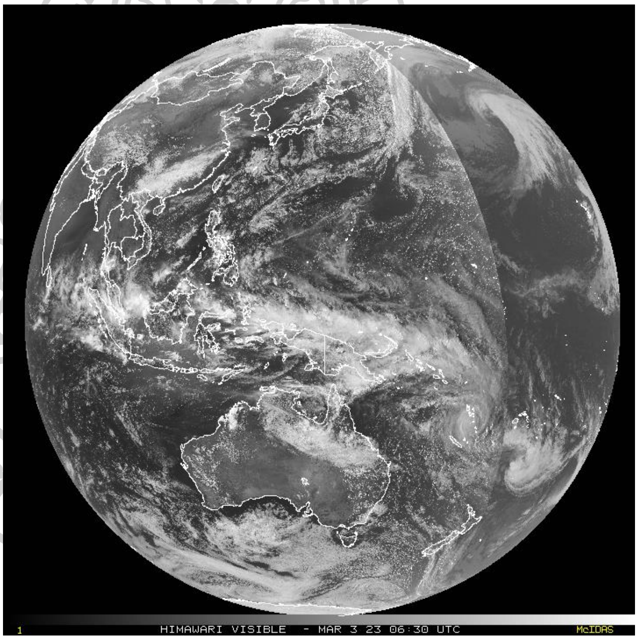

Figure 31 The visible images taken from Himawari-8 satellite.

The rectified images were displayed in a cylindrical projection with the spatial resolution of 3 km × 3 km (Figure 32) (Janjai et al., 2005). Then, nine pixels centered at the position of a solar monitoring station were used to calculate the pseudo-reflectivity (ρ') and it was divided by cosine of local solar zenith angle to get the earth-atmosphere reflectivity (ρ'_{EA}).

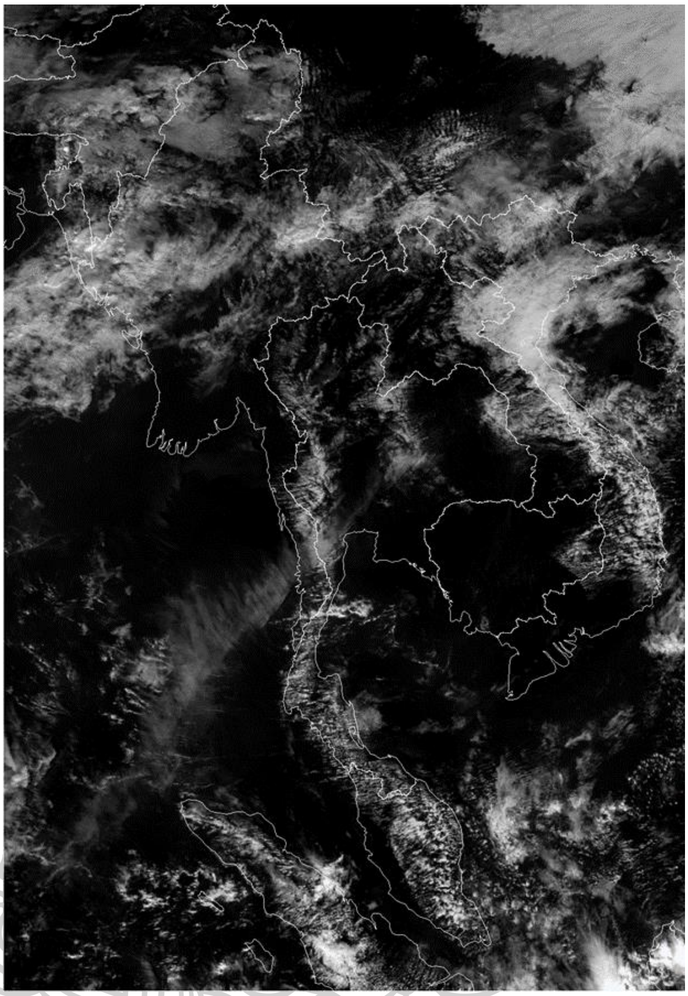

Figure 32 The cylindrical projection of the visible images taken from Himawari-8 satellite.

The earth-atmosphere reflectivity was used to obtain minimum reflectivity (ρ'_{min}) and maximum reflectivity (ρ'_{max}) of the area. The (ρ'_{min}) is the lowest earth-atmosphere reflectivity of that hour and (ρ'_{max}) is the highest earth-atmosphere reflectivity. Afterwards, hourly values of ρ'_{EA}, ρ'_{min}, and ρ'_{max} from January 2017 to December 2021 were used to calculate the cloud index (n) by using the Equation (3.4) given by Cano et al. (1986) as:

$$n = \frac{\rho'_{EA} - \rho'_{min}}{\rho'_{max} - \rho'_{min}} \tag{3.4}$$

where n = satellite derived-cloud index (-).

ρ'_{EA} = the earth-atmosphere reflectivity (-).

ρ'_{min} = the lowest earth-atmosphere reflectivity (-).

ρ'_{max} = the maximum earth-atmosphere reflectivity (-).

3.1.2. Formulation of the model

We assumed that global spectral solar radiation under all-sky conditions comes from the global spectral solar radiation under clear-sky conditions modified by clouds. As a result, we proposed a model for calculating global spectral solar irradiance ($\dot{I}_{g,\lambda}$) as a multiplication of two functions, namely global spectral solar irradiance under clear-sky condition ($\dot{I}_{g,\lambda,clear}$) and cloud modification function (C_{λ}). The model can be written in the form of an equation as:

$$\dot{I}_{g,\lambda} = \dot{I}_{g,\lambda,clear} \cdot C_{\lambda} \quad (3.5)$$

where $\dot{I}_{g,\lambda}$ = global spectral solar irradiance under all-sky conditions (W/m^2/μm).

$\dot{I}_{g,\lambda,clear}$ = global spectral solar irradiance under clear-sky conditions (W/m^2/μm).

C_{λ} = cloud modification function.

The details of $\dot{I}_{g,\lambda,clear}$ and C_{λ} are described in the following sections

3.1.2.1 Global spectral solar irradiance under clear sky conditions

Based on the information in Iqbal (1983) the atmospheric constituents involved in the model under clear sky conditions are aerosols, ozone, water vapor, and nitrogen dioxide. Therefore, we propose a semi-empirical model, which means that the physical parameters affecting the spectrum are involved empirically in the model. The proposed model has the following form:

$$\dot{I}_{g,clear,\lambda} = a_0 \dot{I}_{o\lambda} \exp[-(a_1 m_a + a_2 AOD m_a + a_3 k_{w\lambda} W m_a + a_4 k_{o\lambda} O_3 m_a + a_5 k_{g\lambda} m_a + a_6 k_{n\lambda} NO_2 m_a) + a_7] \quad (3.6)$$

where $\dot{I}_{g,clear,\lambda}$ = spectral global irradiance under clear sky conditions (W/m^2/μm^1)

$\dot{I}_{o\lambda}$ = spectral extraterrestrial irradiance (W/m^2/μm^1)

m_a = air mass (-)

AOD = aerosol optical depth (-)

W = precipitable water (cm)

O_3 = amount of ozone (cm)

NO_2 = amount of nitrogen dioxide (cm)

$k_{w\lambda}$ = spectral extinction coefficients due to water vapor (cm^{-1})

$k_{o\lambda}$ = spectral extinction coefficients due to ozone (cm^{-1})

$k_{g\lambda}$ = spectral extinction coefficients due to gases (-)

$k_{n\lambda}$ = spectral extinction coefficients due to nitrogen dioxide (-); and

$a_1, a_2, a_3, a_4, a_5, a_6$, and a_7 are empirical coefficients.

$k_{w\lambda}, k_{o\lambda}$, and $k_{g\lambda}$ were obtained from Iqbal (1983)

$k_{n\lambda}$ was acquired from Gueymard (1995). The calculation of m_a was based on the formula proposed by Kasten (1966). The detail of the model is shown in appendix 1.

3.1.2.2 The cloud modification function

We assumed that cloud modification function (C_λ) was the ratio of the measured global spectral irradiance under all-sky conditions to the calculated global spectral irradiance under clear sky conditions ($\frac{\dot{I}_{g,\lambda,meas}}{\dot{I}_{g,\lambda,clear}}$) and cloud index for each wavelength. Examples of the relationship between $\frac{\dot{I}_{g,\lambda,meas}}{\dot{I}_{g,\lambda,clear}}$ and cloud index at 0.35, 0.40, 0.50, 0.70, and 0.95 µm are shown in Figure 33-37.

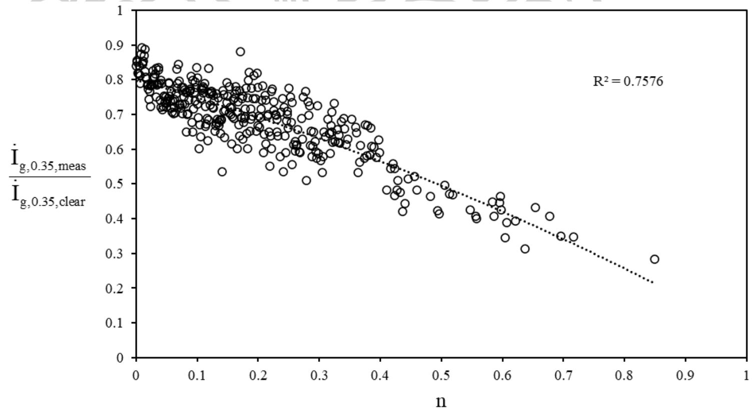

Figure 33 The relationship between $\frac{\dot{I}_{g,\lambda,meas}}{\dot{I}_{g,\lambda,clear}}$ and cloud index at 0.35 µm.

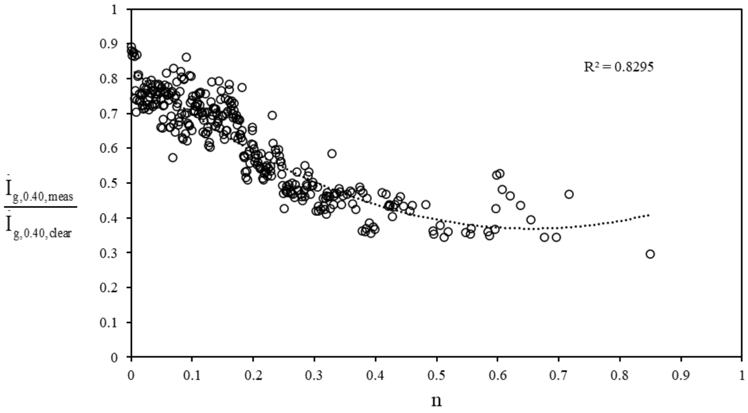

Figure 34 The relationship between $\frac{\dot{I}_{g,\lambda,meas}}{\dot{I}_{g,\lambda,clear}}$ and cloud index at 0.40 µm.

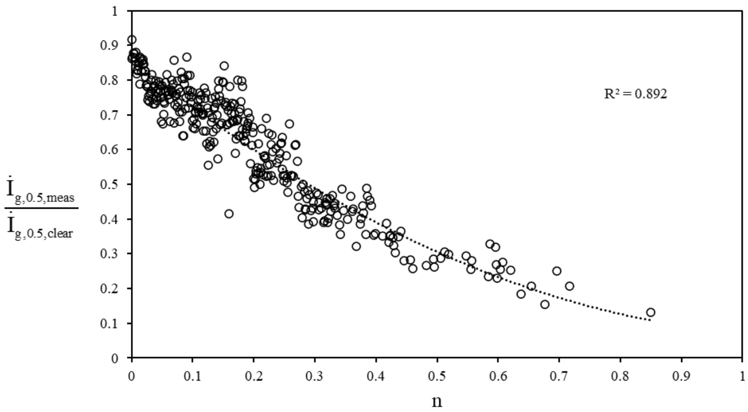

Figure 35 The relationship between $\frac{\dot{I}_{g,\lambda,meas}}{\dot{I}_{g,\lambda,clear}}$ and cloud index at 0.50 µm.

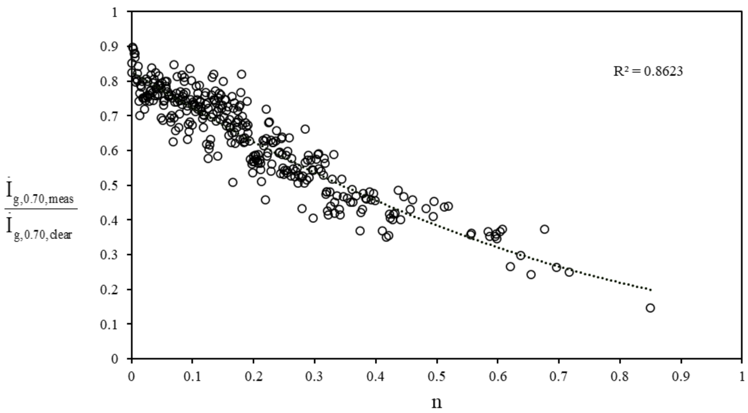

Figure 36 The relationship between $\frac{\dot{I}_{g,\lambda,meas}}{\dot{I}_{g,\lambda,clear}}$ and cloud index at 0.70 µm.

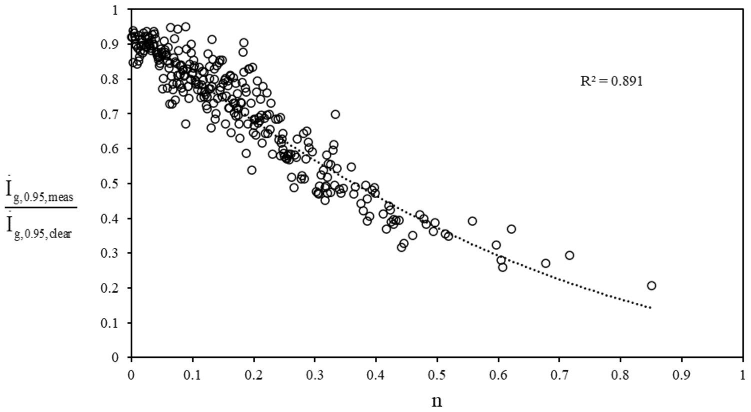

Figure 37 The relationship between $\frac{\dot{I}_{g,\lambda,meas}}{\dot{I}_{g,\lambda,clear}}$ and cloud index at 0.95 µm.

In general, C_λ depends on the cloud index and wavelength. therefore, we proposed C_λ to have the following from:

$$C_\lambda = \frac{\dot{I}_{g,\lambda,meas}}{\dot{I}_{g,\lambda,clear}} = b_{0,\lambda} + b_{1,\lambda} n + b_{2,\lambda} n^2 + b_{3,\lambda} \lambda + b_{4,\lambda} \lambda^2 \quad (3.7)$$

where C_λ = cloud modification function.

$\dot{I}_{g,\lambda,meas}$ = global spectral irradiance under all-sky conditions from the measurement (W/m²/µm).

$\dot{I}_{g,\lambda,clear}$ = global spectral irradiance under clear sky conditions from the model (Equation 3.6) (W/m²/µm).

n = satellite derived-cloud index (-).

λ = wavelength (µm)

$b_{0,\lambda}, b_{1,\lambda}, b_{2,\lambda}, b_{3,\lambda}$ and $b_{4,\lambda}$ = empirical coefficients.

3.1.3 Determination of the model coefficients

Empirical coefficients were obtained from the analytical statistics using statistical software namely, STATISTICA.

In this study, the ratio of measured the global spectral irradiance under all-sky conditions and calculated the global spectral irradiance under clear sky conditions from the model from 4 stations namely, the Chiang Mai, Ubon Ratchathani, Nakhon Pathom, and Songkhla stations were expressed as a function of the cloud index obtained from the satellite data at 9:00 A.M. to 3:00 P.M in January, 2017 – December, 2020 and wavelength were used for regression analysis technique to estimation coefficient of the model.

Table 1 Values of empirical coefficients for every 0.01 µm of the proposed model.

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.350	-15.989	0.166	-1.064	-9.849	164.469
0.360	-6.530	0.055	-0.926	-3.276	64.973
0.370	26.455	-0.032	-0.814	-29.127	-109.137
0.380	42.595	-0.159	-0.561	-131.628	56.528
0.390	-18.189	-0.149	-0.566	43.965	11.491
0.400	2.984	-0.074	-0.707	15.633	-53.333
0.410	-2.174	-0.129	-0.614	21.799	-35.984
0.420	-4.923	-0.185	-0.523	-8.448	52.063
0.430	-6.553	-0.161	-0.573	238.392	-515.108
0.440	-6.485	0.019	-0.839	-3.801	45.789
0.450	-7.680	-0.010	-0.794	20.332	-3.740
0.460	0.916	-0.030	-0.786	30.538	-67.322
0.470	20.555	-0.039	-0.769	20.642	-133.709
0.480	26.628	-0.018	-0.832	-36.394	-36.624
0.490	-2.275	-0.006	-0.854	-12.811	38.624
0.500	3.696	-0.028	-0.813	12.225	-36.341
0.510	9.194	0.005	-0.862	-2.938	-26.833
0.520	-0.014	0.006	-0.886	-15.104	31.758
0.530	8.736	0.012	-0.863	0.537	-29.610
0.540	-1.569	0.022	-0.904	17.289	-24.175
0.550	7.880	0.040	-0.936	2.955	-29.057
0.560	0.887	0.041	-0.935	14.914	-27.187
0.570	-4.155	0.007	-0.908	17.604	-15.841
0.580	26.071	0.027	-0.937	-34.026	-16.666
0.590	-7.064	-0.100	-0.762	-3.182	27.846
0.600	-2.945	-0.033	-0.852	-10.584	27.880
0.610	0.507	0.002	-0.866	-14.112	23.700
0.620	-6.108	0.007	-0.890	-5.505	26.633
0.631	7.827	-0.009	-0.877	4.102	-24.348
0.651	2.535	-0.039	-0.842	12.796	-23.933
0.671	8.433	0.052	-0.947	2.879	-21.407
0.691	5.271	-0.154	-0.732	8.615	-21.924
0.711	-11.291	-0.069	-0.805	8.066	12.414
0.731	-8.658	-0.043	-0.924	-1.271	19.335
0.751	-0.986	0.072	-0.921	14.711	-16.573
0.771	-9.268	0.098	-0.978	-0.623	17.590
0.791	8.970	-0.058	-0.789	3.231	-17.282

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.811	-6.479	-0.082	-0.751	-5.950	18.284
0.830	-7.376	-0.095	-0.795	-5.205	18.023
0.850	-2.752	-0.014	-0.817	-10.082	16.642
0.870	12.332	0.024	-0.860	8.325	-24.950
0.890	7.030	-0.009	-0.816	-14.726	8.550
0.910	-5.308	-0.218	-0.670	-7.834	15.909
0.930	-5.207	-0.529	-0.159	-8.408	15.941
0.950	-8.950	-0.338	-0.711	14.102	-4.086

* The values of the coefficients of the proposed model for every 0.001 μm are shown in Appendix 4.

3.1.4 Model validation

In validating the model, the obtained model (Equation 3.5) was used to compute the global spectral irradiance under all-sky conditions at the four stations for the year 2021. Hourly averages of global spectral irradiance obtained from the model were compared with the data of spectroradiometer (EKO, MS-710, 711). An agreement between the values obtained from the model and measurements was calculated in the form of percentage of mean bias difference relative to mean measured value (MBD) and percentage of root mean square difference relative to mean measured value (RMSD) (Equation 3.8, 3.9)

$$\mathrm{MBD} = \frac{\sum_{i=1}^{N}\sqrt{\frac{(\dot{I}_{g,\lambda,model} - \dot{I}_{g,\lambda,meas})^2}{N}}}{\sum_{i=1}^{N}\frac{\dot{I}_{g,\lambda,meas}}{N}} \times 100\% \qquad (3.8)$$

$$\mathrm{RMBD} = \frac{\sum_{i=1}^{N}\frac{(\dot{I}_{g,\lambda,model} - \dot{I}_{g,\lambda,meas})}{N}}{\sum_{i=1}^{N}\frac{\dot{I}_{g,\lambda,meas}}{N}} \times 100\% \qquad (3.9)$$

where $\dot{I}_{model}$ = global spectral irradiance calculated from the model ($W/m^2/\mu m$).

$\dot{I}_{meas}$ = global spectral irradiance obtained from measurements ($W/m^2/\mu m$).

N = number of data.

The results were also compared with the spectral irradiance from the measurements at 4 stations for each wavelength band. The comparison is shown in Figure 38-41.

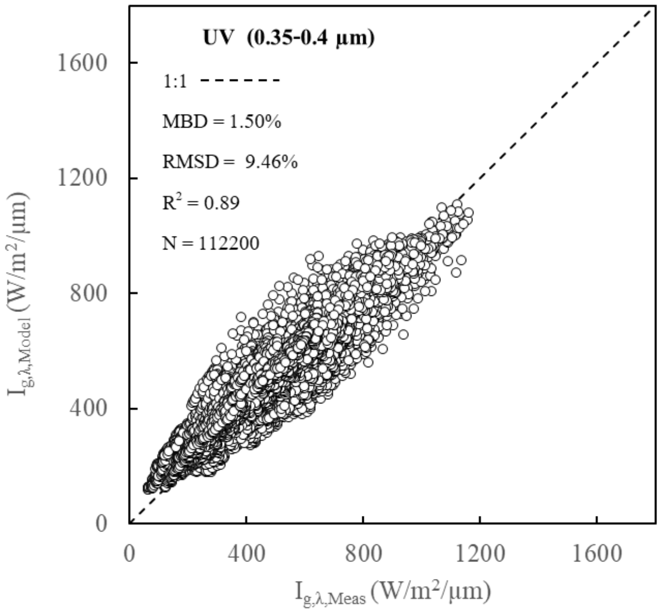

Figure 38 The comparison result of the spectral values calculated from the model ($I_{g,\lambda,Model}$) and those from the measurements ($I_{g,\lambda,Meas}$) in the ultraviolet wavelengths (UV band)

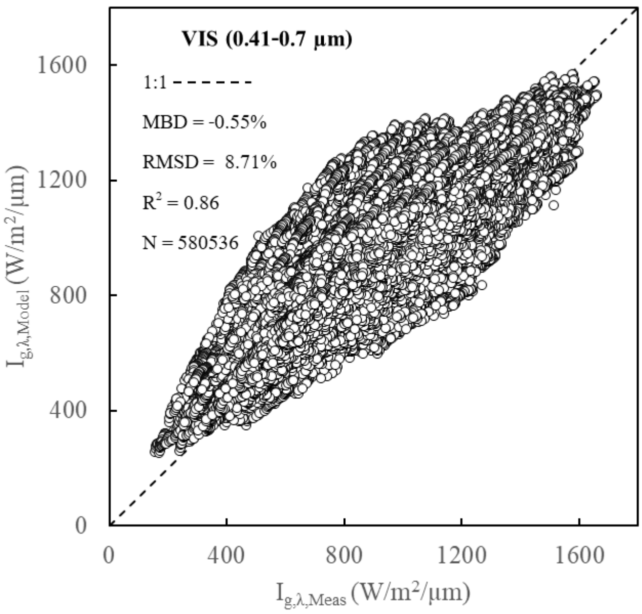

Figure 39 The comparison result of the spectral values calculated from the model ($I_{g,\lambda,Model}$) and those from the measurements ($I_{g,\lambda,Meas}$) in the visible wavelengths (VIS band)

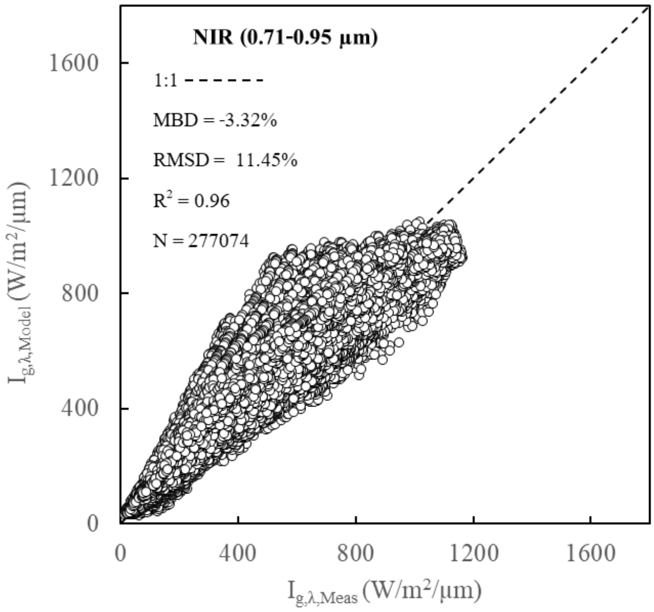

Figure 40 The comparison result of the spectral values calculated from the model ($I_{g,\lambda,Model}$) and those from the measurements ($I_{g,\lambda,Meas}$) in the near-infrared wavelengths (NIR band)

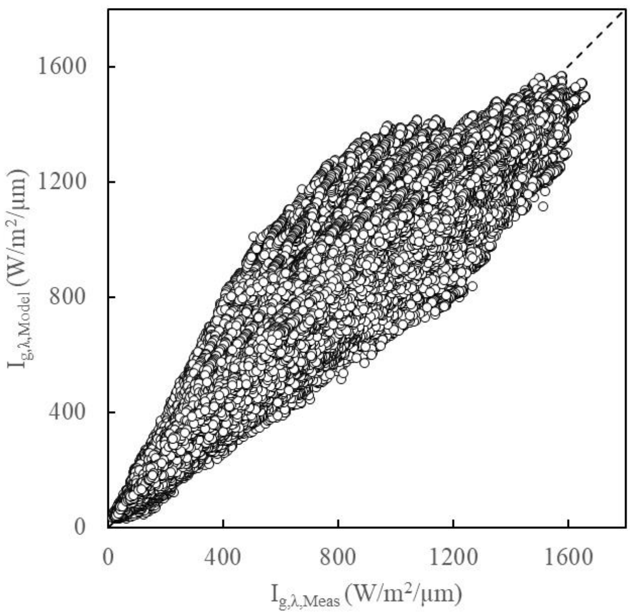

Figure 41 The comparison result of the spectral values calculated from the model ($I_{g,\lambda,Model}$) and those from the measurements ($I_{g,\lambda,Meas}$) in all wavelengths.

Table 2 Results of the comparison for each wavelengths band.

Wavelength range	**MBD (%)**	**RMSD (%)**
Ultraviolet wavelengths (UV)	1.50	9.46
Visible wavelengths (VIS)	-0.55	8.71
Near-infrared wavelengths (NIR)	-3.32	11.45
All wavelengths	-0.96	9.48

Figure. 33-36 and Table 2, show comparison of the spectral values calculated from the model and measurements available in the ultraviolet (UV, 350-400 nm), visible (VIS, 401-700 nm), near-infrared (NIR, 701-950 nm) bands and all wavelengths (350-950 nm). As shown in Figure 33-36, it was found that the discrepancy in terms of the RMSD and MBD was found to be 8.71-11.45% and -3.32-1.50%, respectively. The UV and NIR bands, the discrepancy in terms of RMSD greater than that of the VIS band. This may be due to the fact that there are less data in these bands, as compared to the data in VIS band and the sensitivities of the instrument in these bands wavelengths are lower than VIS wavelengths band.

However, the comparison for each station (Figure 42-45) shows also the good agreement.

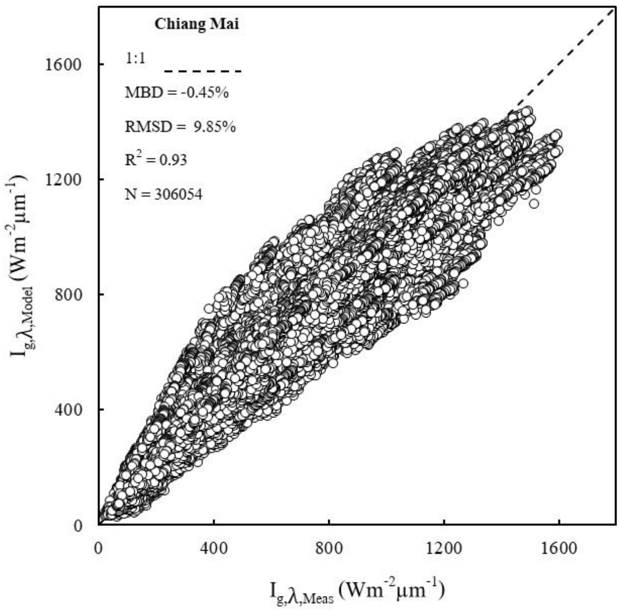

Figure 42 The comparison of the spectral values calculated from the model ($I_{g,\lambda,Model}$) and measurements ($I_{g,\lambda,Meas}$) for the year 2021 of Chiang Mai station.

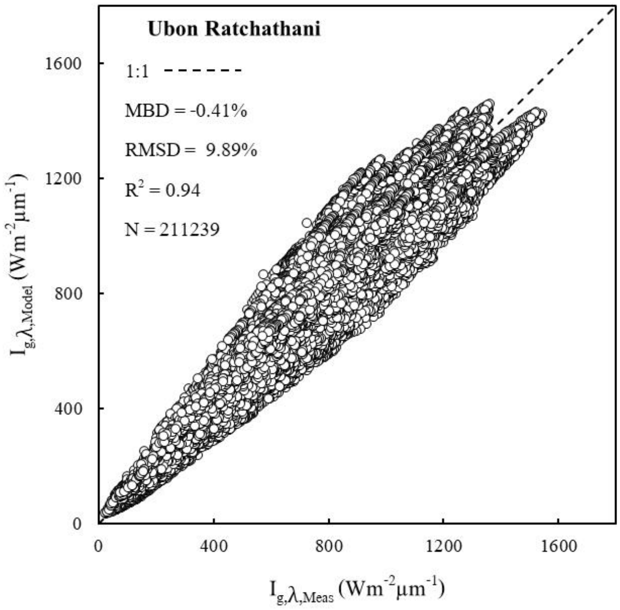

Figure 43 The comparison of the spectral values calculated from the model ($I_{g,\lambda,Model}$) and measurements ($I_{g,\lambda,Meas}$) for the year 2021 of Ubon Ratchathani station.

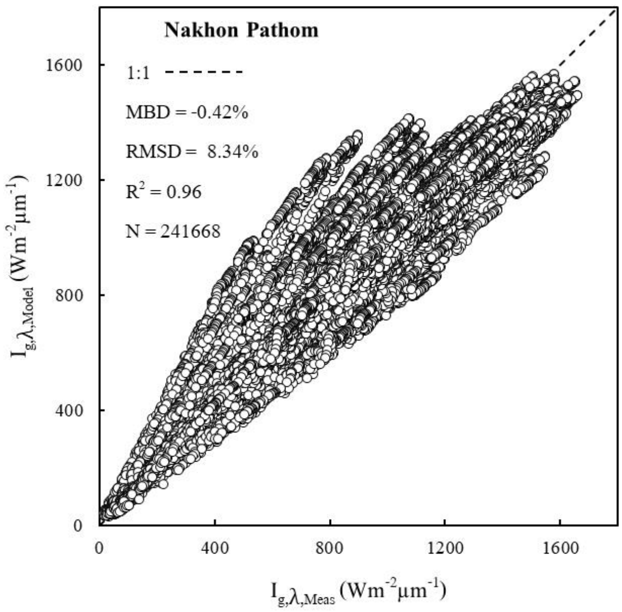

Figure 44 The comparison of the spectral values calculated from the model ($I_{g,\lambda,Model}$) and measurements ($I_{g,\lambda,Meas}$) for the year 2021 of Nakhon Pathom station.

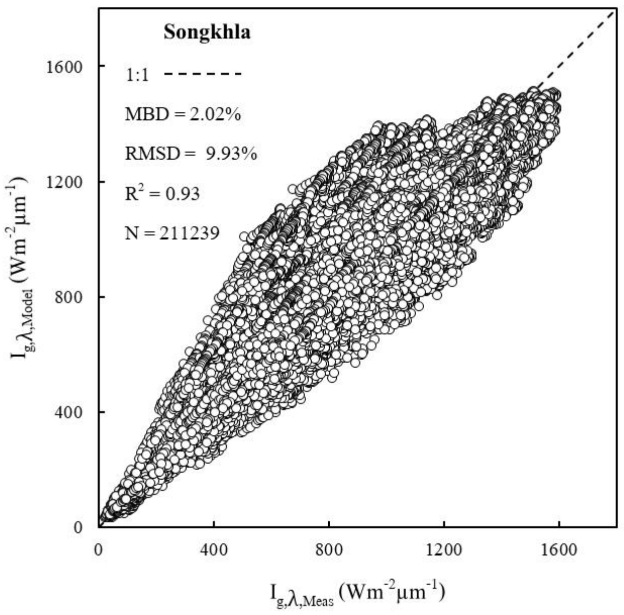

Figure 45 The comparison of the spectral values calculated from the model ($I_{g,\lambda,Model}$) and measurements ($I_{g,\lambda,Meas}$) for the year 2021 of Songkhla station.

Table 3 Results of the comparison for each station.

Stations	**MBD (%)**	**RMSD (%)**
Chiang Mai	-0.45	9.85
Ubon Ratchathani	-0.41	9.89
Nakhon Pathom	-0.42	8.34
Songkhla	-2.02	9.93

From Figure 37-40 and Table 3, it was found that the discrepancy in terms of the RMSD and MBD was 8.34-9.93% and -0.45 - -2.02%, respectively. We can clearly see that the RMSD and MBD values are very low. Example of global spectral solar irradiance from the model and from measurements under all-sky conditions at different times at each measurement station. It is clearly seen that the spectrum from the model agrees well with that from the measurement (Figure 41-44).

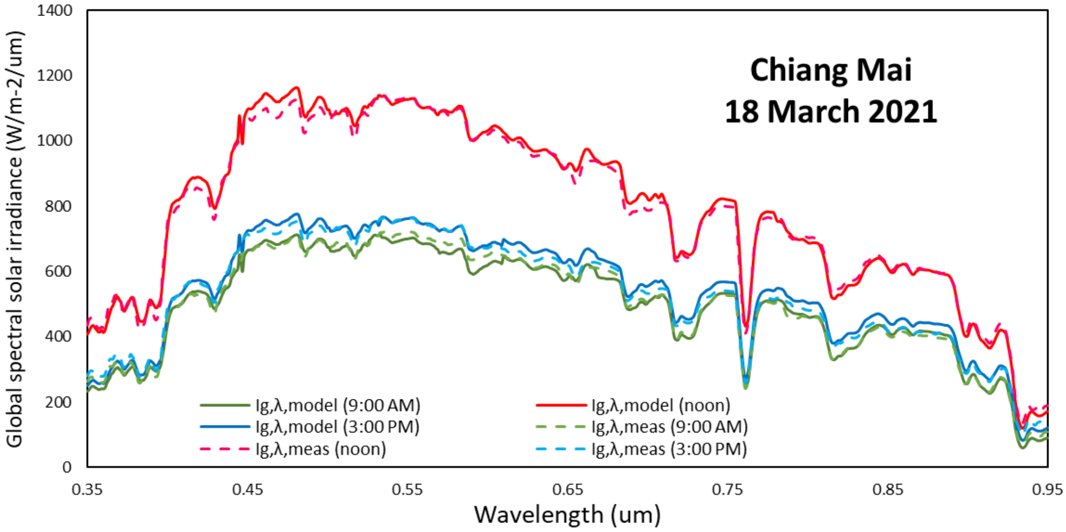

Figure 46 Examples of global spectral solar irradiance calculated from the model and the measurement at Chiang Mai station at 9 A.M., noon and 3 P.M.

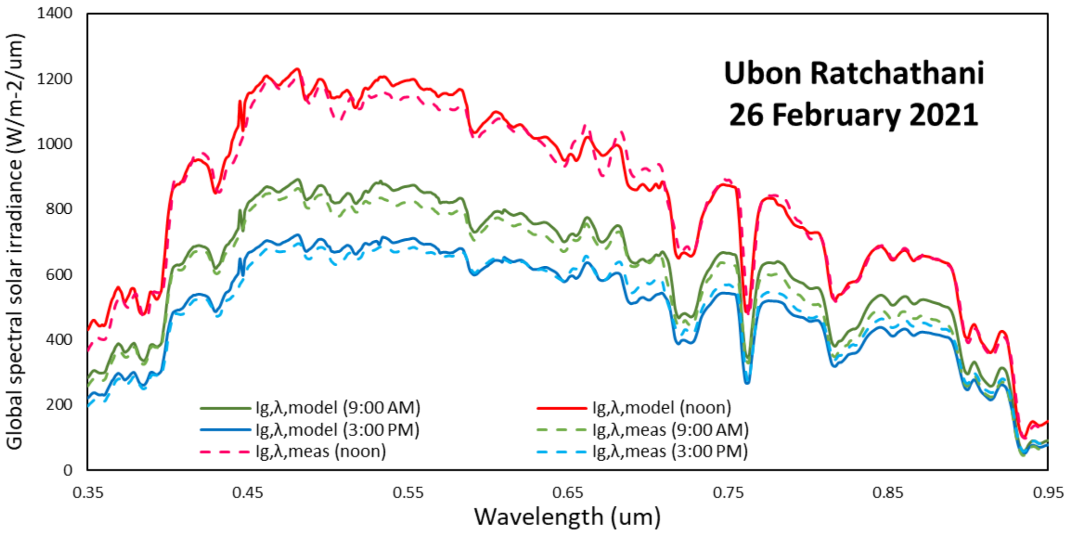

Figure 47 Examples of global spectral solar irradiance calculated from the model and the measurement at Ubon Ratchathani station at 9 A.M., noon and 3 P.M.

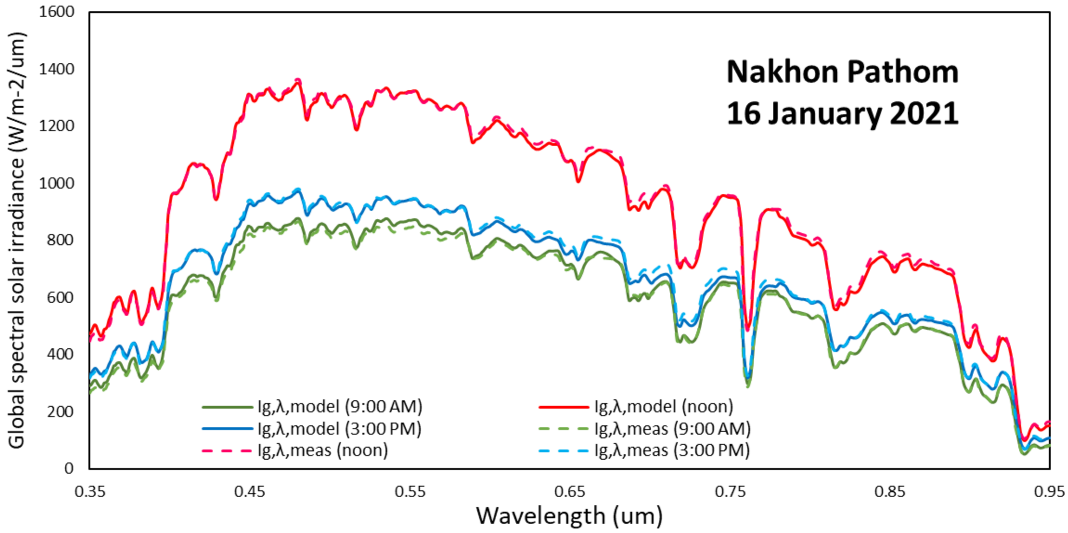

Figure 48 Examples of global spectral solar irradiance calculated from the model and the measurement at Nakhon Pathom station at 9 A.M., noon and 3 P.M.

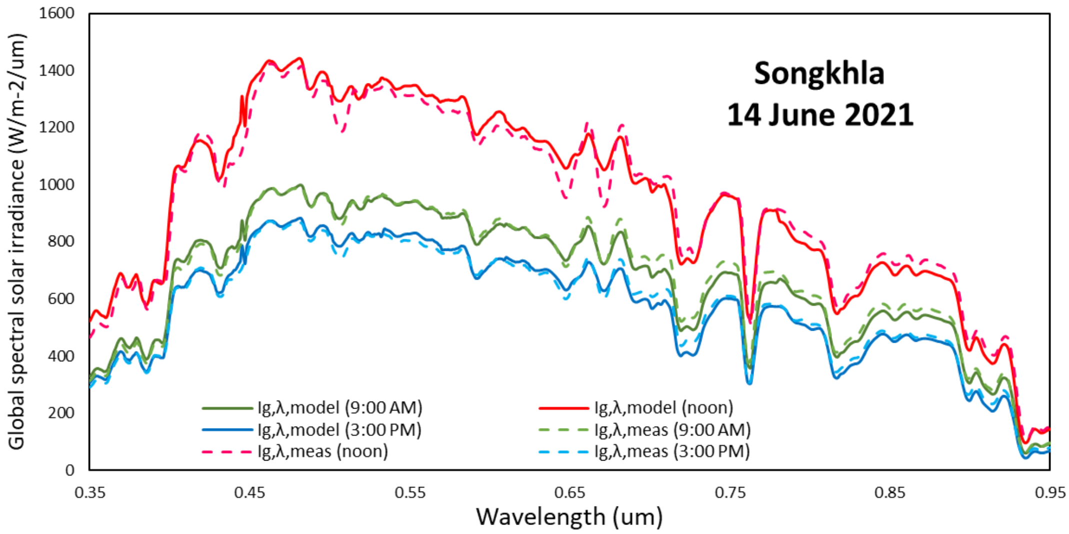

Figure 49 Examples of global spectral solar irradiance calculated from the model and the measurement at Songkhla station at 9 A.M., noon and 3 P.M.

Chapter 4

Conclusion

In this study, a model for computing spectral solar irradiance under all-sky conditions in Thailand has been developed. The spectral irradiance is equal to the multiplication of two functions namely, a clear sky spectral irradiance function and a cloud modification function. The first function was obtained from the model to estimate global spectral irradiance under clear-sky conditions. The second function is the ratio of the measured global spectral irradiance under all-sky conditions and the calculated global spectral irradiance under clear-sky conditions written as a polynomial function of satellite-derived cloud index and wavelength. To create the model, the spectral data from four stations in the main regions of Thailand, namely Chiang Mai station (18. 77˚ N, 98. 97˚ E) in the North, Ubon Ratchathani station (15. 25˚ N, 104. 87˚ E) in the Northeast, Nakhon Pathom station (13. 82˚ N, 100. 04˚ E) in the Center, and Songkhla station (7. 18˚ N, 100.60˚ E) in the South were collected and separated into two groups. The first group (January, 2017- December, 2020) was employed for modeling and the second group (January- December, 2021) for validating the model. From the validation against the independent data, it was found that the model can predict the global spectral irradiance in the UV and NIR bands the discrepancy in terms of RMSD greater than that of the VIS band. This may be due to the fact that there are less data in these bands, as compared to the data in VIS band and the sensitivities of the instrument in these bands wavelengths are lower than VIS wavelengths. For all wavelengths (350-950 nm), the discrepancy in terms of the root mean square difference (RMSD) of 9.48%, and the mean bias difference (MBD) of -0.96%, as compared to the measurements. The result of the comparison between global spectral irradiance from the measurement at four stations in the main regions of Thailand can be observed that the spectrum from the model agrees well with that from the measurements. Accordingly, we conclude that the model can be used to calculate global spectral irradiance in Thailand.

Recommendation

As the measurement of global spectral solar irradiance in Thailand is very limited, it is recommended that more measurements stations should be made, and the data should be used to improve the performance of the model.

Appendix 1

A semi-empirical model for calculating global spectral solar irradiance under clear sky conditions in Thailand[2]

1. Instrument and data

To develop the model, the spectral data of global solar radiation are required. As Thailand can be divided into four main regions, namely, the northern, northeastern, central and the southern regions, four spectroradiometers were installed at Chiang Mai, Ubon Ratchathani, Nakhon Pathom and Songkhla, respectively (Fig. 1). These spectroradiometers were regularly calibrated by EKO, the manufacturer. At these stations, AERONET sunphotometers (AErosol RObotic NETwork) were also installed to measure direct solar irradiance at the following wavelengths: 340, 380, 440, 500, 675, 870, 1020 and 1640 nm. The spectral irradiance values at these wavelengths were sent via the internet to the AERONET headquarters in the USA for processing, and the optical properties of aerosols were obtained. The obtained properties were posted in the AERONET website (https://aeronet.gsfc.nasa.gov/). These sunphotometers were routinely calibrated by AERONET. In this study, data on aerosol optical depth (AOD) at 340, 380, 440, 500, 675, 870 and 1020 nm, as well as precipitable water (W) ozone amount (O_3) and nitrogen dioxide amount (NO_2) information were downloaded from the AERONET website and subsequently used for model development. The positions and pictorial view of instruments installed and used in this study are shown in Fig. 1.

[2] Part of this appendix has been published in the Journal of Renewable Energy and Smart Grid Technology 17 (2022) 9-15.

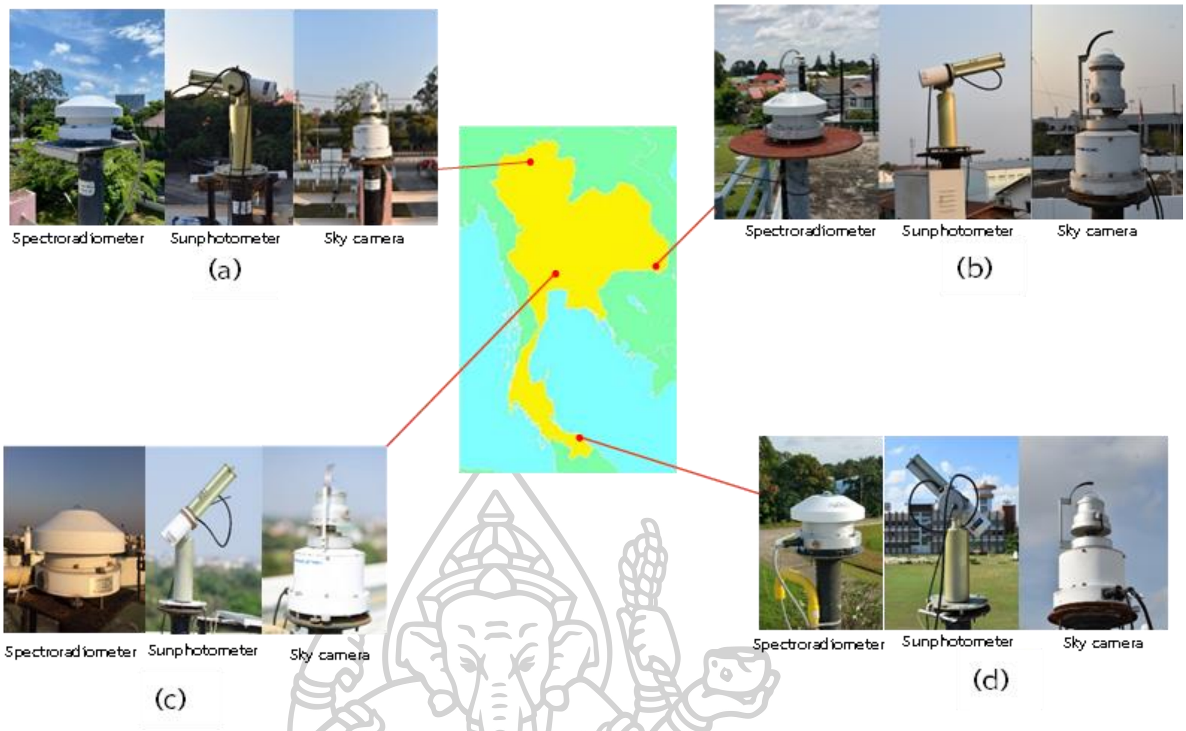

Fig. 1 Positions and pictorial view of instruments installed and used in this study (a) Chiang Mai station, (b) Ubon Ratchathani station, (c) Nakhon Pathom station and (d) Songkhla station.

2. Formulation of the model

Based on the information in Iqbal [19], the atmospheric constituents involved in the model under clear sky conditions are aerosols, ozone, water vapor, and nitrogen dioxide. Therefore, we propose a semi-empirical model, which mean that the physical parameters affecting the spectrum are involved empirically in the model. The proposed model has the following form:

$$\dot{I}_{g,clear,\lambda} = a_0 \dot{I}_{o\lambda} \exp[-(a_1 m_a + a_2 AOD m_a + a_3 k_{w\lambda} W m_a + a_4 k_{o\lambda} O_3 m_a + a_5 k_{g\lambda} m_a + a_6 k_{n\lambda} NO_2 m_a) + a_7] \quad (1)$$

where $\dot{I}_{g,clear,\lambda}$ = spectral global irradiance under clear sky conditions ($Wm^{-2}\mu m^{-1}$);

$\dot{I}_{o\lambda}$ = spectral extraterrestrial irradiance ($Wm^{-2}\mu m^{-1}$);

m_a = air mass (-);

AOD = aerosol optical depth (-);

W = precipitable water (cm);

O_3 = amount of ozone (cm);

NO_2 = amount of nitrogen dioxide (cm);

$k_{w\lambda}$ = spectral extinction coefficients due to water vapour (cm^{-1});

$k_{o\lambda}$ = spectral extinction coefficients due to ozone (cm^{-1});

$k_{g\lambda}$ = spectral extinction coefficients due to gases (-);

$k_{n\lambda}$ = spectral extinction coefficients due to nitrogen dioxide (-); and

a_0 , a_1, a_2, a_3, a_4, a_5, a_6 and a_7 are empirical coefficients.

$k_{w\lambda}$, $k_{o\lambda}$, and $k_{g\lambda}$ were obtained from Iqbal [19]

$k_{n\lambda}$ was acquired from Gueymard [20]. The calculation of m_a was based on the formula proposed by Kasten [21].

The values of empirical coefficients are obtained by fitting the Eq. (1) with the measured data from the four stations. The values of the coefficients for every 0.01 μm are shown in Table 1.

Table 1 Values of empirical coefficients for every 0.01 μm of the proposed model.

wavelength(μm)	Coefficients*							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.350	0.279	0.479	0.275	0.000	203.850	-17.810	0.000	1.547
0.360	0.276	0.796	0.278	0.000	0.000	-9.382	0.000	1.654
0.370	0.287	0.704	0.260	0.000	0.000	42.213	0.000	1.694
0.380	0.235	0.661	0.248	0.000	0.000	63.254	0.000	1.823
0.390	0.243	0.719	0.263	0.000	0.000	25.462	0.000	1.742
0.400	0.313	0.781	0.273	0.000	0.000	-14.620	0.000	1.493
0.410	0.000	0.714	0.259	0.000	0.000	18.630	0.000	8.907
0.420	0.360	0.663	0.250	0.000	0.000	46.356	0.000	1.531
0.430	0.339	0.676	0.252	0.000	0.000	38.709	0.000	1.894
0.440	0.258	0.298	0.245	0.000	12976.000	-7.984	0.000	1.904
0.450	0.336	0.262	0.244	0.000	622.490	11.647	0.000	1.556
0.460	0.748	0.211	0.238	0.000	315.560	50.158	0.000	0.858
0.470	0.167	0.177	0.236	0.000	220.780	73.495	0.000	2.418
0.480	0.341	0.212	0.239	0.000	137.060	57.980	0.000	1.658
0.490	0.305	0.225	0.244	0.000	91.558	51.971	0.000	1.711
0.500	0.572	0.231	0.235	0.000	62.958	92.888	0.000	1.158
0.510	0.313	0.253	0.246	0.000	50.288	9.627	0.000	1.704
0.520	0.560	0.208	0.241	0.000	41.030	106.020	0.000	1.164
0.530	0.554	0.231	0.247	0.000	31.935	63.466	0.000	1.157
0.540	0.212	0.222	0.248	0.000	27.337	105.590	0.000	2.199
0.550	0.329	0.230	0.253	0.000	24.255	57.593	0.000	1.714
0.560	0.355	0.221	0.256	0.000	20.454	103.640	0.000	1.623
0.570	0.256	0.220	0.260	0.000	18.091	89.135	2.759	2.003
0.580	0.509	0.217	0.259	0.000	18.102	181.010	0.177	1.284
0.590	0.293	0.075	0.246	0.000	22.912	438.080	0.223	1.833
0.600	0.300	-0.039	0.255	0.000	25.955	469.340	0.079	1.800
0.610	0.180	-0.017	0.253	0.000	24.491	912.460	0.000	2.303
0.620	0.311	-0.004	0.256	0.000	27.457	698.650	0.000	1.718
0.630	0.232	-0.015	0.256	0.000	33.143	1164.900	0.000	2.042

wavelength(μm)	Coefficients*							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.650	0.322	-0.134	0.252	0.000	50.057	949.780	0.000	1.684
0.670	0.176	45.654	0.283	-2.000	66.136	-1289.000	1.248	2.269
0.690	0.255	-0.598	0.239	3.250	119.220	6034.500	-0.409	1.922
0.710	0.273	0.069	0.314	0.000	160.150	0.000	-0.053	1.838
0.730	0.472	-0.057	0.308	0.000	324.700	0.000	0.023	1.385
0.750	0.282	-0.107	0.278	0.000	411.290	0.000	-2.116	1.813
0.770	0.271	1.094	0.290	-4.800	959.800	0.000	-99.450	1.846
0.790	0.131	0.716	0.351	0.000	0.000	0.000	0.560	2.608
0.810	0.237	0.751	0.371	0.000	0.000	0.000	0.035	2.055
0.830	0.392	0.764	0.401	0.000	0.000	0.000	0.051	1.529
0.850	0.168	0.685	0.378	0.000	0.000	0.000	0.041	2.343
0.870	0.426	0.670	0.401	0.000	0.000	0.000	-1.031	1.361
0.890	0.164	0.694	0.399	0.000	0.000	0.000	0.004	2.346
0.910	0.091	0.858	0.454	0.000	0.000	0.000	0.014	3.012
0.930	0.019	1.078	0.452	0.000	0.000	0.000	0.005	4.430
0.950	0.025	1.171	0.501	0.000	0.000	0.000	0.006	4.381

* The values of the coefficients of the proposed model for every 1 nm are shown in Appendix 3.

3. Validation of the model

In validating the model, the obtained model (Eq.1) was used to compute the spectral global irradiance under clear sky conditions at the four stations for the year 2021. The results were compared with the spectral from the measurements. The comparison of the spectral values calculated from the model and measurements is shown in Fig. 2.

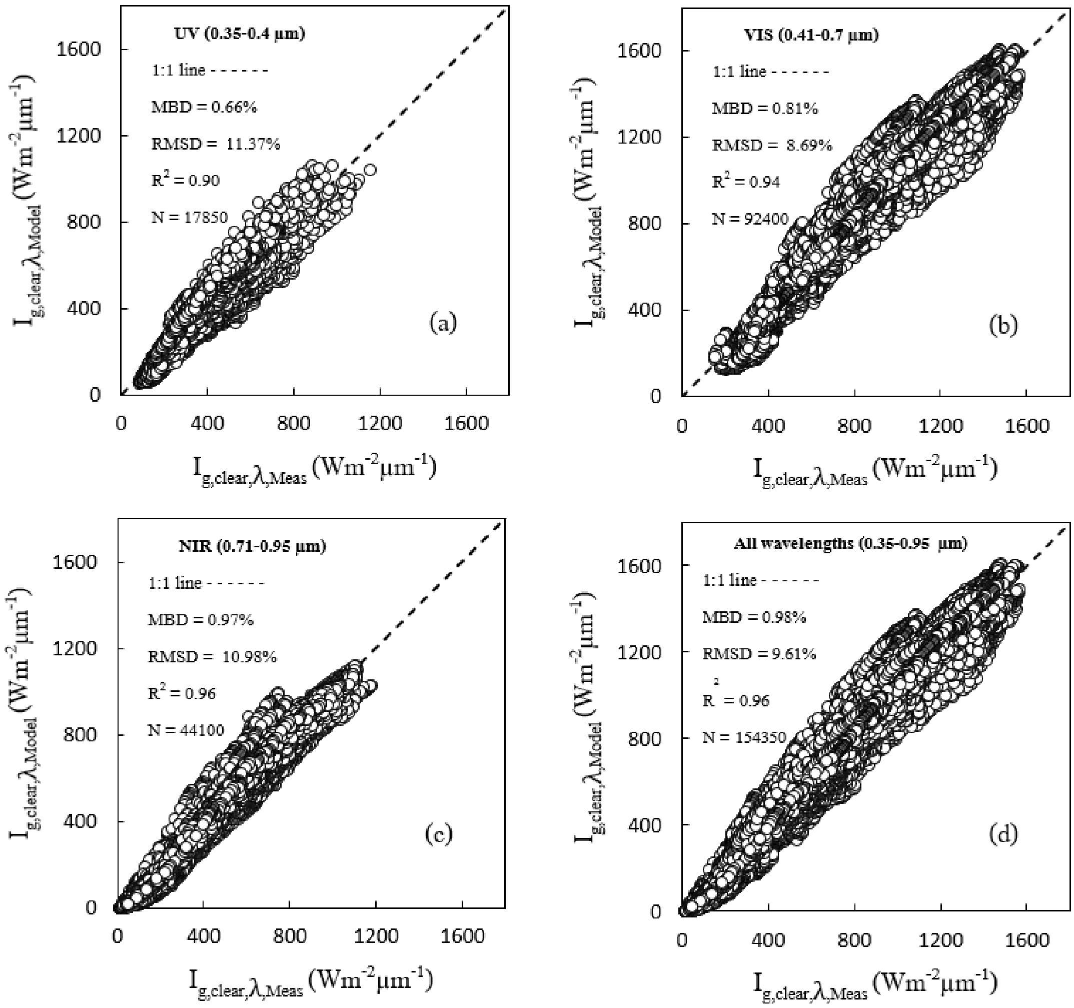

Fig. 2 The comparison result of the spectral values calculated from the model ($I_{g,clear,\lambda,Model}$) and those from the measurements ($I_{g,clear,\lambda,Meas}$); (a) in the ultraviolet wavelengths (UV band), (b) in the visible wavelengths (VIS band), (c) in the near-infrared wavelengths (NIR band) and (d) in all wavelengths. (RMSD = percentage of root mean square difference relative to mean measured value, MBD = percentage of mean bias difference relative to mean measured value, R^2 = coefficient of determination and N = number of data.)

Fig. 2, presents the results of the comparison of different wavelengths. As can be seen, for the UV and NIR wavelengths, the RMSD and MBD are relatively high as the sensitivities of the measurements in these wavelengths are not high. Meanwhile, the VIS wavelengths have the lowest RMSD, which may be due to the fact that there are more data (N= 92400) and the sensitivities of the instrument in these wavelengths are higher than those in UV and NIR wavelengths. However, for the whole data, RMSD and MBD are 9.61% and 0.98%, respectively, and are actually quite low. The comparison for each station is shown in Fig 3. From this figure, it can be clearly seen that the RMSD and MBD values are quite low. Examples of the global spectral solar irradiance from the model and that from the measurements at different times at each monitoring stations are shown in Fig. 4. From Fig. 4, it can be observed that the spectrum from the model agree well with that from the measurements, indicating that the model presents quite accurate solar spectrum values.

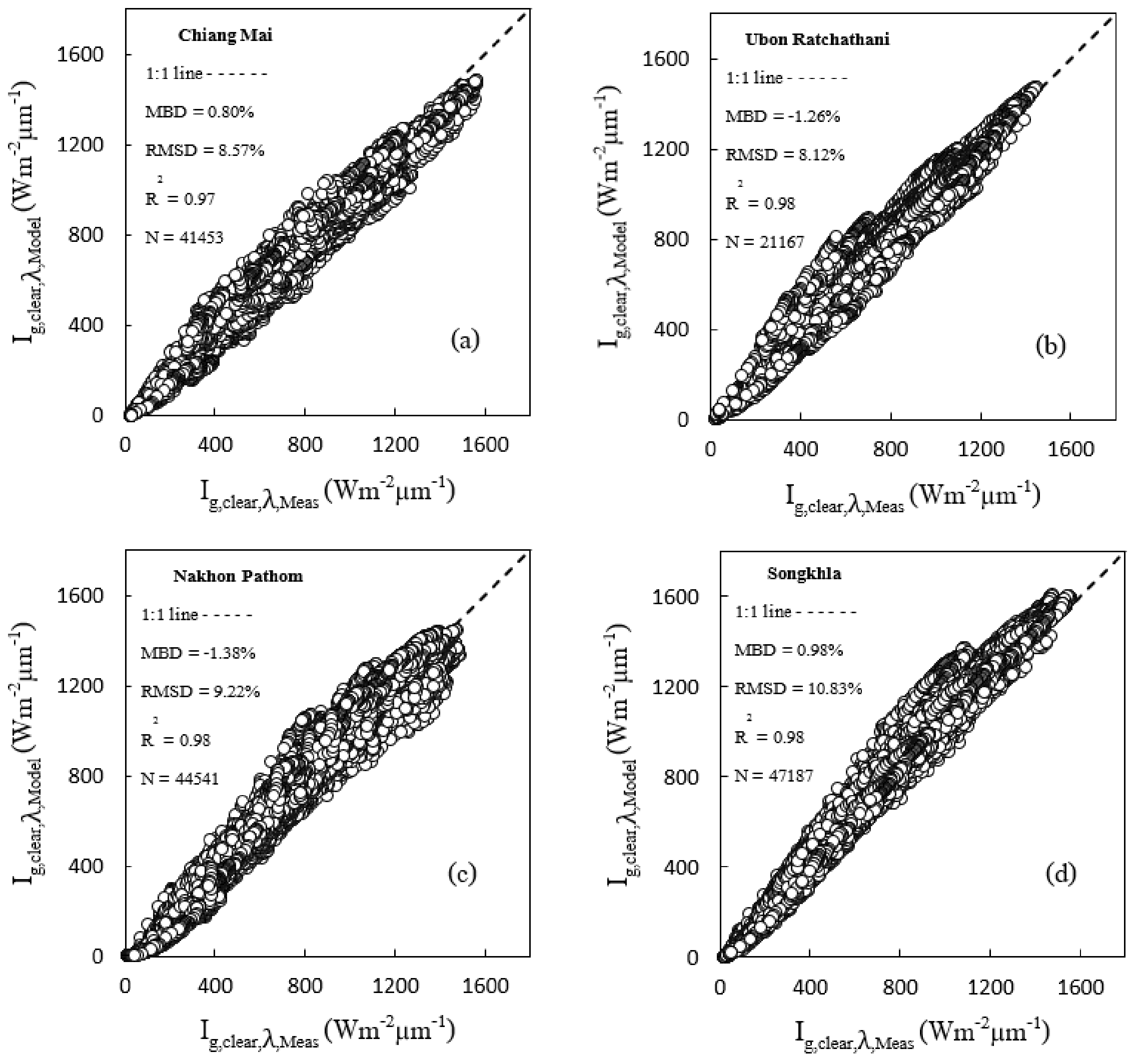

Fig. 3 The comparison of the spectral values calculated from the model ($I_{g,clear,\lambda,Model}$) and measurements ($I_{g,clear,\lambda,Meas}$) at the four stations for the year 2021 for all wavelengths (a) Chiang Mai station, (b) Ubon Ratchathani station, (c) Nakhon Pathom station and (d) Songkhla station.

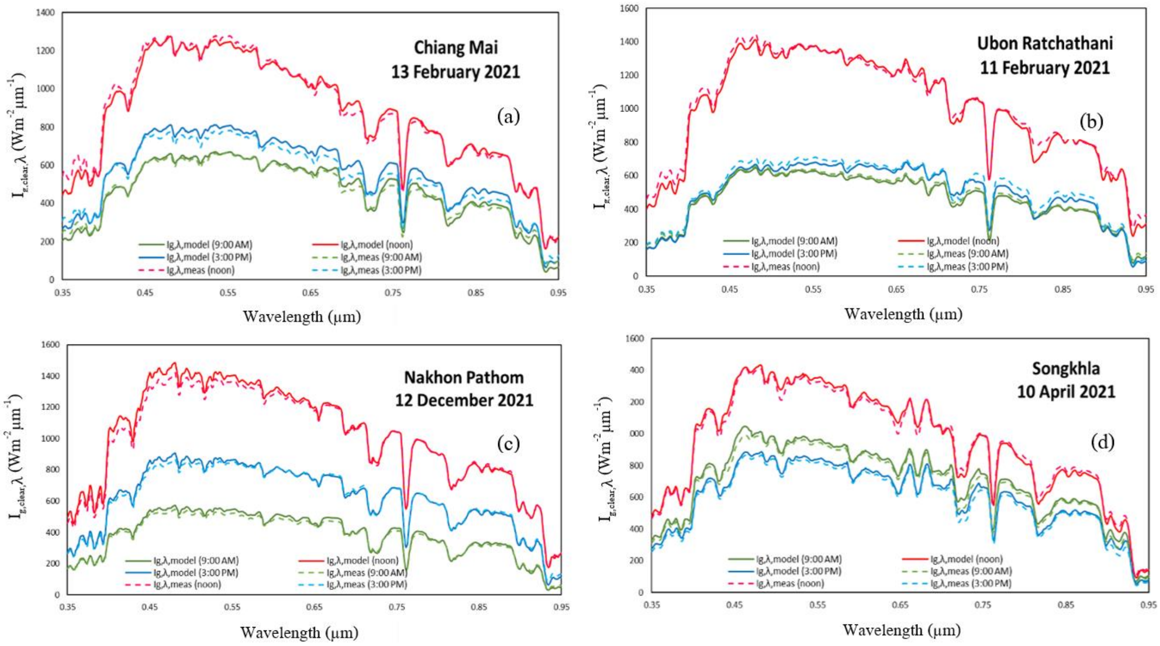

Fig. 4 Examples of spectral global solar irradiance calculated from the model ($I_{g,\lambda,model}$) and the measurement ($I_{g,\lambda,meas}$) at the solar monitoring stations at 9 A.M., noon and 3 P.M. (a) Chiang Mai station, (b) Ubon Ratchathani station, (c) Nakhon Pathom station and (d) Songkhla station.

4. Conclusion

A semi-empirical model for calculating spectral global irradiance in Thailand under clear sky conditions was developed in this work. The model expresses the spectrum as an empirical function of various atmospheric constituents namely aerosol optical depth, ozone amount, precipitation water and the amount of nitrogen dioxide. The model was validated against the independent data and the validation results show good agreement between the spectrum calculated from the model and that obtained from the measurements. The discrepancies in terms of RMSD and MBD reach 9.61% and 0.98%, respectively for the whole data.

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Appendix 2

A model for the estimation of global spectral solar irradiance under all-sky conditions for Nakhon Pathom station, Thailand[3]

1. Methodology

The methodology used in this study consists mainly of several processes namely, measurements, a formulation of the model, and a model validation. The details of these processes are presented as follows.

2. Measurements

2.1. Measurement of solar spectrum

The global spectral irradiance was measured using a spectroradiometer (EKO, model MS-710) (figure 1.) at a solar monitoring station (13.82˚N, 100.04˚E) situated at Silpakorn University in Nakhon Pathom, Thailand. This measurement place is called Nakhon Pathom station. The spectroradiometer waveband extends from 0.35 to 0.95 µm. The resolution of the spectrum is 0.001 µm for the wavelength 0.35 – 0.63 µm and 0.002 µm for the wavelength 0.63 – 0.95 µm. The 1-minute data collected from the instrument were averaged over 1-hour period. The hourly values of spectral solar irradiance from January 2017 to December 2019 were employed for creating the model and the data from January to December 2020 were used for model validation.

Figure 1. EKO MS-710 spectroradiometer installed at Nakhon Pathom station.

[3] Part of this appendix has been published in Journal of Physics: Conference Series (Vol. 2431(2023), 1-4.

2.2. Measurements of aerosol, precipitable water, ozone and nitrogen dioxide

To create the spectral model, it is necessary to have data of aerosols, precipitable water, ozone and nitrogen dioxide. These data were obtained from an AERONET sunphotometer installed at the same station.

2.3. Satellite data

In this work, visible images taken from Himawari satellite were used to provide information on clouds over the Nakhon Pathom station. The raw visible images were transformed to the rectified images using the process described in Janjai *et al*. [9]. The rectified images were displayed in a cylindrical projection with the spatial resolution of 3 km × 3 km. Then, nine pixels centered at the position of solar monitoring station were used to calculate the pseudo-reflectivity (ρ') and it was divided by cosine of local solar zenith angle to get the earth-atmosphere reflectivity (ρ'_{EA}).

The earth-atmosphere reflectivity was used to obtain minimum reflectivity (ρ'_{min}) ρand maximum reflectivity (ρ'_{max}) of the area. The ρ'_{min} is the lowest earth-atmosphere reflectivity of that hour and ρ'_{max} is the highest earth-atmosphere reflectivity. Afterwards, hourly values of ρ'_{EA}, ρ'_{min} and ρ'_{max} from January 2017 to December 2020 were used to calculate the cloud index (n) by using the equation given by Cano *et al*. [10] as:

$$n = \frac{\rho'_{EA} - \rho'_{min}}{\rho'_{max} - \rho'_{min}} \tag{1}$$

3. Formulation of the model

We assumed that global spectral solar radiation under all-sky conditions comes from the global spectral solar radiation under clear-sky condition modified by clouds. As a result, we proposed a model for calculating global spectral solar irradiance ($\dot{I}_{g,\lambda,all}$) as a multiplication of two functions, namely global spectral solar irradiance under clear-sky condition ($\dot{I}_{g,\lambda,clear}$) and cloud modification function (C_λ). The model can be written in the form of an equation as:

$$\dot{I}_{g,\lambda,all} = \dot{I}_{g,\lambda,clear} \cdot C_\lambda \tag{2}$$

$\dot{I}_{g,\lambda,clear}$ for Nakhon Pathom station can be written as:

$$\dot{I}_{g,\lambda,clear} = b_0 \dot{I}_{0\lambda} \exp[-(b_1 + b_2 AOD + b_3 k_g + b_4 k_o O_3 + b_5 k_n NO_2 + b_6 k_w W) m_a + b_7] \tag{3}$$

where $\dot{I}_{g,\lambda,clear}$ = global spectral solar irradiance under clear sky condition ($Wm^{-2}\mu m^{-1}$)
$\dot{I}_{0\lambda}$ = extraterrestrial spectral solar irradiance ($Wm^{-2}\mu m^{-1}$)
AOD = optical depth of aerosols at 500 nm (-)
O_3 = amount of ozone (cm)
NO_2 = amount of nitrogen dioxide (cm)
W = precipitable water (cm)
m_a = air mass or relative optical air mass (-) [1]
k_n = coefficient of extinction by nitrogen dioxide (-) [6]
k_g = coefficient of extinction by mixed gases (-) [3]
k_o = coefficient of extinction by ozone (-) [3]
k_w = coefficient of extinction by water vapour (-) [3]
b_0, b_1, b_2, b_3, b_4, b_5, b_6 and b_7 = empirical coefficients

The values of AOD, O_3, NO_2, and W were obtained from a sunphotometer of AERONET installed at the same station. The data are available at the website: https://aeronet.gsfc.nasa.gov/. After fitting with the data, b_0-b_7 were obtained and they are available https://docs.google.com/spreadsheets/d/1oLjWOsPkUoEbyqmGuba ZtKGrMTiTcrAY/edit#gid=183105867.

For the second function (C_λ), it is obtained from the measured data under all-sky conditions, and it can be written as:

$$C_\lambda = \frac{\dot{I}_{g,\lambda,all}}{\dot{I}_{g,\lambda,clear}} = C_0 + C_1 n + C_2 n^2 + C_3\lambda + C_4\lambda^2 \quad (4)$$

where n = satellite-derived cloud index (-)
λ = wavelength (μm)

C_0, C_1, C_2, C_3 and C_4 = empirical coefficients; C_0= 1.25, C_1= -1.11, C_2= 0.34, C_3= -1.43 and a_4= 1.11

4. Model validation

The model for calculating global solar irradiance under all-sky conditions (Eq. 2) was used to compute global solar irradiance under all-sky conditions for the year 2020 and the result were compared to the measurement. It was found that the discrepancy in terms of percentage of root mean square difference relative to the mean measured value (RMSD) and percentage of mean bias difference relative to the mean measured value (MBD) was 14.21% and 4.85%, respectively. The comparison of seasonal average value of the global spectral irradiance are shown in figure 2.

From figure 2, it is clearly seen that the spectrum from the model agree well with that from the measurement.

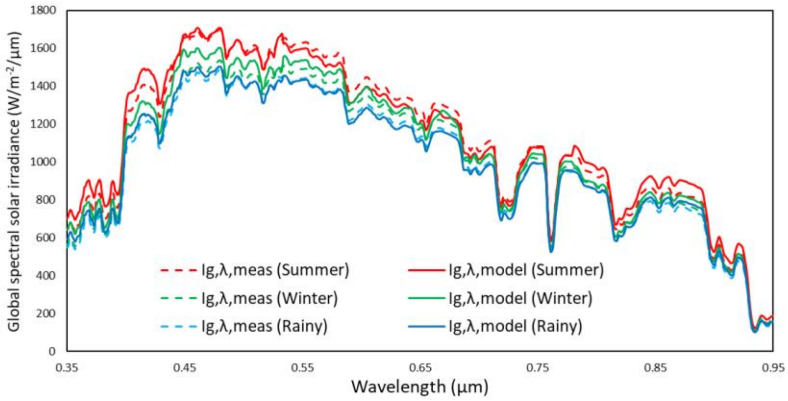

Figure 2. Comparison of global spectral solar irradiance from the model ($\dot{I}_{g,\lambda,model}$) and the measurement (average for the summer, winter and rainy seasons at noon time) ($\dot{I}_{g,\lambda,meas}$). The season period is given by Thai Meteorological Department of Thailand (www.tmd.go.th).

5. Conclusions

In this study, a model for computing the global spectral solar irradiance under all-sky conditions was developed. The validation was undertaken against the ground-based global spectral solar irradiance data collected in 2020. The measured spectral global irradiance and that calculated from the model are in reasonable agreement, with the discrepancy in terms of root mean square difference (RMSD) and mean bias difference (MBD) of 14.21% and 4.85%, respectively.

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Appendix 3

The value of the model coefficients for clear sky

The value of the model coefficients for every 0.001 µm of the model for calculating global spectral irradiance under clear sky conditions.

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.350	0.2787	0.4789	0.2749	0	203.85	-17.805	0	1.5474
0.351	0.3011	0.4686	0.2718	0	236.46	-20.552	0	1.561
0.352	0.3313	0.4517	0.2723	0	278.78	-18.21	0	1.5613
0.353	0.4205	0.4686	0.2728	0	298.24	-9.3448	0	1.2155
0.354	0.2815	0.5123	0.2696	0	298.57	-2.8114	0	1.5484
0.355	0.1449	0.5189	0.2655	0	328.11	11.382	0	2.2656
0.356	0.7657	0.5187	0.2648	0	405.79	16.678	0	0.723
0.357	0.3308	0.522	0.2628	0	546.89	19.482	0	1.6878
0.358	0.3755	0.5334	0.2653	0	922.66	12.24	0	1.6956
0.359	0.2974	0.5673	0.2691	0	2740.4	-6.2452	0	1.573
0.36	0.2758	0.7955	0.2779	0	0	-9.382	0	1.6536
0.361	0.3707	0.8005	0.2784	0	0	-14.073	0	1.4716
0.362	0.733	0.788	0.2794	0	0	-9.8922	0	0.6997
0.363	0.4355	0.7872	0.2785	0	0	-11.661	0	1.2537
0.364	0.5298	0.7931	0.2771	0	0	-14.7	0	1.0753
0.365	0.3747	0.7726	0.2782	0	0	-1.1004	0	1.3382
0.366	0.516	0.7586	0.2756	0	0	8.0452	0	0.9748
0.367	0.3098	0.7442	0.2716	0	0	14.041	0	1.5516
0.368	0.3417	0.7293	0.2695	0	0	24.315	0	1.5463
0.369	0.3497	0.7237	0.2665	0	0	28.596	0	1.4273
0.37	0.2868	0.7041	0.2603	0	0	42.213	0	1.6935
0.371	0.2708	0.7035	0.2587	0	0	40.926	0	1.7014
0.372	0.2655	0.6896	0.2584	0	0	50.044	0	1.8067

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.373	0.5512	0.6882	0.2581	0	0	50.057	0	1.1884
0.374	0.3692	0.7168	0.2622	0	0	31.687	0	1.6057
0.375	0.3532	0.7523	0.2705	0	0	10.646	0	1.4919
0.376	0.7522	0.7579	0.2719	0	0	8.0902	0	0.7381
0.377	0.4352	0.7678	0.272	0	0	2.5391	0	1.1365
0.378	0.363	0.7454	0.2685	0	0	15.582	0	1.2963
0.379	0.2973	0.7013	0.2621	0	0	39.338	0	1.7241
0.380	0.2353	0.6609	0.2481	0	0	63.254	0	1.8228
0.381	0.6272	0.6423	0.2461	0	0	77.552	0	0.9185
0.382	0.3181	0.6451	0.247	0	0	76.279	0	1.8595
0.383	0.3092	0.6715	0.2525	0	0	57.411	0	1.9979
0.384	0.3167	0.7175	0.2606	0	0	30.402	0	1.6169
0.385	0.2864	0.7432	0.2649	0	0	14.845	0	1.6514
0.386	0.3393	0.7592	0.2702	0	0	3.7075	0	1.4915
0.387	0.4899	0.7695	0.2714	0	0	-4.7031	0	1.1503
0.388	0.3663	0.7659	0.276	0	0	-1.1874	0	1.5152
0.389	0.264	0.7608	0.2696	0	0	1.3788	0	1.7013
0.390	0.2432	0.7192	0.2632	0	0	25.462	0	1.7419
0.391	0.2702	0.6825	0.2541	0	0	43.174	0	1.5582
0.392	0.2974	0.6512	0.2516	0	0	60.823	0	1.7286
0.393	0.3211	0.6348	0.2488	0	0	70.903	0	2.2035
0.394	0.2892	0.6654	0.2519	0	0	53.995	0	1.7388
0.395	0.3776	0.7193	0.2595	0	0	22.356	0	1.2227
0.396	0.3388	0.7542	0.273	0	0	3.5651	0	1.7815
0.397	0.2898	0.8018	0.277	0	0	-26.677	0	1.9191
0.398	0.4619	0.8117	0.2783	0	0	-30.915	0	1.0344
0.399	0.2655	0.8132	0.2834	0	0	-26.931	0	1.6017

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.400	0.3133	0.7812	0.2733	0	0	-14.62	0	1.4933
0.401	0.2671	0.7542	0.2709	0	0	-1.4914	0	1.6698
0.402	0.349	0.7055	0.2641	0	0	26.217	0	1.4509
0.403	0.4343	0.6758	0.2538	0	0	40.897	0	1.2999
0.404	0.2839	0.6668	0.2508	0	0	44.422	0	1.7395
0.405	0.2954	0.6692	0.2503	0	0	44.539	0	1.7058
0.406	0.5567	0.6809	0.2521	0	0	40.576	0	1.1184
0.407	0.7626	0.6903	0.2534	0	0	33.114	0	0.7742
0.408	0.3435	0.7012	0.2553	0	0	25.02	0	1.5095
0.409	0.4123	0.7095	0.2585	0	0	21.17	0	1.3416
0.410	0.0002	0.7138	0.2593	0	0	18.63	0	8.9067
0.411	0.2576	0.7122	0.2595	0	0	20.252	0	1.7778
0.412	0.2527	0.7145	0.2604	0	0	18.624	0	1.8256
0.413	0.3197	0.7028	0.2584	0	0	24.064	0	1.6242
0.414	0.2962	0.6966	0.2577	0	0	28.972	0	1.7207
0.415	0.2753	0.685	0.2559	0	0	38.304	0	1.8045
0.416	0.3649	0.6729	0.2531	0	0	45.949	0	1.4718
0.417	0.8214	0.6636	0.2513	0	0	49.13	0	0.7607
0.418	0.2749	0.6643	0.2512	0	0	47.599	0	1.8452
0.419	0.5621	0.6628	0.2511	0	0	46.926	0	1.1207
0.420	0.36	0.663	0.2504	0	0	46.356	0	1.5312
0.421	0.2976	0.6657	0.2502	0	0	45.042	0	1.6957
0.422	0.3406	0.6604	0.2492	0	0	47.654	0	1.6841
0.423	0.3483	0.6574	0.2487	0	0	48.22	0	1.5799
0.424	0.3388	0.6613	0.2486	0	0	47.652	0	1.5688
0.425	0.3121	0.6617	0.2479	0	0	52.647	0	1.6835
0.426	0.3037	0.6623	0.2485	0	0	54.639	0	1.6965

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.427	0.7025	0.6574	0.2469	0	0	52.468	0	0.912
0.428	0.2864	0.6405	0.2425	0	0	63.389	0	1.7718
0.429	0.2929	0.6597	0.247	0	0	54.102	0	1.7911
0.430	0.3391	0.6761	0.2515	0	0	38.709	0	1.8941
0.431	0.3174	0.7175	0.2568	0	0	14.947	0	1.5666
0.432	0.1847	0.7409	0.2616	0	0	1.5763	0	2.1408
0.433	0.2388	0.7605	0.2668	0	0	-9.4019	0	1.8484
0.434	0.3422	0.7569	0.2657	0	0	-9.2586	0	1.5456
0.435	0.3649	0.7408	0.2646	0	0	-0.2363	0	1.4775
0.436	0.2924	0.7362	0.2632	0	0	3.3897	0	1.6035
0.437	0.3131	0.7315	0.2614	0	0	6.6795	0	1.6067
0.438	0.4662	0.7309	0.2621	0	0	5.2592	0	1.3523
0.439	0.4272	0.7478	0.264	0	0	-4.714	0	1.295
0.440	0.2581	0.2979	0.2452	0	12976	-7.9839	0	1.9044
0.441	0.3146	0.3185	0.2494	0	4319.6	-21.921	0	1.597
0.442	0.2731	0.3069	0.2489	0	2684.3	-25.455	0	1.7263
0.443	0.3329	0.3034	0.2485	0	1883.2	-16.139	0	1.5783
0.444	0.2605	0.2977	0.2487	0	1470.8	-12.39	0	1.8014
0.445	0.2754	0.2743	0.2461	0	1238.3	-8.2183	0	1.8387
0.446	0.3494	0.2752	0.2461	0	1023.2	-2.0716	0	1.5775
0.447	0.2927	0.2882	0.2479	0	880.73	-7.544	0	1.6775
0.448	0.31	0.2688	0.2466	0	799.68	-4.9502	0	1.6877
0.449	0.2946	0.2764	0.2476	0	689.55	1.512	0	1.731
0.450	0.336	0.2617	0.2439	0	622.49	11.647	0	1.5563
0.451	0.3268	0.2587	0.2427	0	551.24	23.792	0	1.6097
0.452	0.0873	0.2479	0.2406	0	500.86	34.124	0	3.0162
0.453	0.2746	0.2392	0.2389	0	462.78	42.698	0	1.8586

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.454	0.3406	0.2427	0.2392	0	425.54	44.473	0	1.6441
0.455	0.2363	0.2443	0.2394	0	401.4	41.715	0	1.9862
0.456	0.3208	0.2408	0.2397	0	380.85	42.402	0	1.6629
0.457	0.3195	0.2333	0.2397	0	359.95	42.096	0	1.661
0.458	0.5582	0.2139	0.2378	0	349.45	47.922	0	1.1724
0.459	0.3231	0.2089	0.2376	0	331.02	52.999	0	1.7062
0.460	0.7475	0.2109	0.2383	0	315.56	50.158	0	0.8583
0.461	0.2676	0.2069	0.2374	0	302.29	55.209	0	1.8823
0.462	0.3592	0.2086	0.2375	0	286.59	52.671	0	1.5657
0.463	0.1793	0.1939	0.2356	0	277.17	58.336	0	2.2902
0.464	0.6591	0.1844	0.2342	0	267.4	71.393	0	1.0179
0.465	0.2774	0.1775	0.2334	0	258.74	83.58	0	1.8466
0.466	0.3112	0.1817	0.2332	0	246.85	77.203	0	1.7876
0.467	0.1987	0.1806	0.2334	0	240.89	70.47	0	2.1811
0.468	0.4559	0.1792	0.2342	0	234.96	74.114	0	1.3562
0.469	0.3715	0.1773	0.235	0	229.82	74.902	0	1.5612
0.470	0.1672	0.1769	0.2357	0	220.78	73.495	0	2.4181
0.471	0.3196	0.1816	0.2369	0	209.67	67.834	0	1.7021
0.472	0.3199	0.1926	0.2379	0	196.91	61.62	0	1.6939
0.473	0.32	0.202	0.239	0	183.47	55.153	0	1.7229
0.474	0.2834	0.2066	0.239	0	174.1	53.098	0	1.819
0.475	0.0896	0.2092	0.2395	0	165.59	60.435	0	2.9917
0.476	0.4547	0.2114	0.2391	0	158.74	65.448	0	1.4007
0.477	0.3157	0.2136	0.2395	0	153.33	63.992	0	1.7094
0.478	0.1392	0.2156	0.24	0	147.93	59.558	0	2.5621
0.479	0.3163	0.2124	0.2399	0	143.89	53.819	0	1.7103
0.480	0.3405	0.2123	0.2394	0	137.06	57.98	0	1.6581

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.481	0.4491	0.2174	0.2385	0	128.52	64.196	0	1.3535
0.482	0.3118	0.2185	0.2366	0	120.62	81.327	0	1.7462
0.483	0.2329	0.2153	0.2338	0	112.1	107.57	0	2.0273
0.484	0.2629	0.2188	0.2334	0	105.75	107.87	0	1.9083
0.485	0.6038	0.1967	0.2311	0	103.28	121.13	0	1.1299
0.486	0.1448	0.1947	0.2339	0	102.76	106.19	0	2.6571
0.487	0.3149	0.2161	0.2379	0	98.824	76.924	0	1.7571
0.488	0.3441	0.2359	0.2427	0	96.155	41.999	0	1.6261
0.489	0.2581	0.2342	0.2445	0	93.61	41.954	0	1.8943
0.490	0.3046	0.2247	0.2444	0	91.558	51.971	0	1.7114
0.491	0.1288	0.2122	0.2432	0	87.639	73.688	0	2.6393
0.492	0.319	0.1959	0.2406	0	85.754	81.515	0	1.7412
0.493	0.3616	0.2071	0.2417	0	81.258	70.579	0	1.6265
0.494	0.2667	0.2125	0.2415	0	78.268	60.669	0	1.8496
0.495	0.2618	0.2161	0.2423	0	75.305	59.495	0	1.9351
0.496	0.3203	0.2114	0.2419	0	73.132	66.573	0	1.6865
0.497	0.525	0.214	0.2419	0	70.152	82.915	0	1.1886
0.498	0.1555	0.211	0.2414	0	67.538	106.99	0	2.4781
0.499	0.5248	0.2166	0.2414	0	65.605	107.55	0	1.1938
0.500	0.5723	0.2306	0.2348	0	62.958	92.888	0	1.1577
0.501	0.1648	0.2271	0.2359	0	62.4	73.373	0	2.4186
0.502	0.1509	0.235	0.2391	0	62.306	37.614	0	2.4531
0.503	0.4427	0.2433	0.242	0	61.751	14.072	0	1.353
0.504	0.4013	0.2515	0.2452	0	60.91	-4.6396	0	1.4832
0.505	0.7356	0.2568	0.2467	0	60.073	-21.175	0	0.8115
0.506	0.4594	0.2609	0.248	0	58.633	-32.029	0	1.2987
0.507	0.4076	0.2559	0.248	0	56.99	-26.861	0	1.4463

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.508	0.3678	0.255	0.248	0	55.054	-19.842	0	1.5452
0.509	0.3274	0.2514	0.2468	0	53.241	-10.367	0	1.6686
0.510	0.3127	0.2526	0.246	0	50.288	9.6273	0	1.7039
0.511	0.335	0.2453	0.2441	0	48.606	28.59	0	1.6139
0.512	0.4155	0.2307	0.2408	0	46.951	61.2	0	1.4714
0.513	0.3145	0.2198	0.2375	0	45.129	105.66	0	1.7529
0.514	0.3258	0.205	0.2335	0	43.968	153.03	0	1.7072
0.515	0.0889	0.1949	0.231	0	42.872	194.1	0	2.9807
0.516	0.3039	0.1835	0.2286	0	41.937	235.03	0	1.8684
0.517	0.3812	0.1783	0.2307	0	41.959	219.34	0	1.5994
0.518	0.167	0.1869	0.2335	0	41.883	161.84	0	2.4645
0.519	0.0002	0.2041	0.238	0	41.622	116.82	0	8.9683
0.520	0.5598	0.2082	0.2405	0	41.03	106.02	0	1.1643
0.521	0.4892	0.2069	0.242	0	40.288	106.06	0	1.2669
0.522	0.0871	0.1905	0.2411	0	40.46	106.3	0	3.0507
0.523	0.2887	0.1983	0.2406	0	38.345	116.99	0	1.8233
0.524	0.3266	0.1998	0.2387	0	36.719	115.43	0	1.669
0.525	0.5809	0.2025	0.2387	0	35.5	105.88	0	1.1045
0.526	0.1421	0.1951	0.2395	0	35.106	111.81	0	2.6536
0.527	0.3399	0.1966	0.2409	0	34.787	102.44	0	1.6972
0.528	0.3369	0.2176	0.2439	0	33.415	84.552	0	1.6748
0.529	0.4358	0.2369	0.2468	0	32.123	67.12	0	1.4107
0.530	0.5536	0.2312	0.2467	0	31.935	63.466	0	1.1574
0.531	0.4669	0.2198	0.246	0	31.663	78.941	0	1.324
0.532	0.195	0.2121	0.2448	0	31.234	92.287	0	2.3027
0.533	0.1601	0.2243	0.2451	0	30.139	95.273	0	2.4201
0.534	0.32	0.2425	0.2484	0	28.578	94.469	0	1.6907

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.535	0.32	0.2425	0.2484	0	28.578	94.469	0	1.6907
0.536	0.3524	0.2438	0.2491	0	28.15	88.249	0	1.653
0.537	0.3864	0.2384	0.2488	0	27.734	97.664	0	1.5518
0.538	0.4673	0.2295	0.248	0	27.621	93.574	0	1.3452
0.539	0.3341	0.2257	0.2471	0	27.406	97.724	0	1.7138
0.540	0.2119	0.2216	0.2481	0	27.337	105.59	0	2.1992
0.541	0.1668	0.2212	0.2494	0	27.349	73.46	0	2.3749
0.542	0.3101	0.225	0.251	0	27.168	47.002	0	1.787
0.543	0.3576	0.2281	0.2522	0	26.855	38.512	0	1.6173
0.544	0.2952	0.2285	0.2528	0	26.555	37.475	0	1.8112
0.545	0.3968	0.2231	0.2524	0	26.358	44.816	0	1.5065
0.546	0.3217	0.2216	0.2522	0	25.925	58.632	0	1.7294
0.547	0.2902	0.2224	0.2518	0	25.536	55.734	0	1.8571
0.548	0.3477	0.225	0.252	0	25.155	51.553	0	1.6594
0.549	0.3522	0.2299	0.2527	0	24.714	48.082	0	1.629
0.550	0.3289	0.23	0.2527	0	24.255	57.593	0	1.7141
0.551	0.3485	0.2302	0.2533	0	23.697	65.635	0	1.6513
0.552	0.1907	0.2291	0.2534	0	23.264	61.357	0	2.2685
0.553	0.3529	0.2275	0.2531	0	22.856	64.035	0	1.6338
0.554	0.3654	0.2277	0.2532	0	22.387	77.064	0	1.5892
0.555	0.0001	0.2315	0.2537	0	21.73	103.73	0	9.5368
0.556	0.1714	0.2235	0.252	0	21.506	133.23	0	2.3775
0.557	0.3605	0.2192	0.2521	0	21.261	140.11	0	1.6139
0.558	0.1722	0.2173	0.2531	0	21.019	139.64	0	2.3806
0.559	0.327	0.216	0.2538	0	20.853	128.89	0	1.7248
0.560	0.355	0.2214	0.2562	0	20.454	103.64	0	1.6225
0.561	0.3234	0.2254	0.2578	0	20.169	69.372	0	1.7273

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.562	0.1733	0.2215	0.2581	0	19.927	74.344	0	2.3394
0.563	0.355	0.2171	0.2578	0	19.763	63.072	0	1.6167
0.564	0.1667	0.2146	0.2575	0	19.468	67.837	0	2.3783
0.565	0.3194	0.2117	0.2566	0	19.341	78.055	0	1.7568
0.566	0.3356	0.2079	0.2565	0	19.265	98.69	0	1.6894
0.567	0.4	0.2133	0.2574	0	18.87	96.701	0	1.4834
0.568	0.1913	0.2052	0.2563	0	18.883	102.16	0	2.26
0.569	0.3181	0.2006	0.2573	0	18.84	103.13	0	1.7234
0.570	0.2564	0.2199	0.2595	0	18.091	89.135	2.7592	2.003
0.571	0.3123	0.2305	0.2615	0	17.918	72.189	1.1805	1.7836
0.572	0.2208	0.2392	0.2631	0	17.722	74.736	0.7042	2.0972
0.573	0.3722	0.2369	0.2637	0	17.913	79.641	0.4814	1.5838
0.574	0.3134	0.2286	0.263	0	18.101	122.61	0.3193	1.7589
0.575	0.3095	0.2125	0.2611	0	18.614	162.6	0.2083	1.786
0.576	0.2964	0.2094	0.2596	0	18.549	243.11	0.1718	1.8193
0.577	0.1851	0.2218	0.2603	0	18.027	262.07	0.1644	2.2842
0.578	0.3098	0.2198	0.2602	0	18.089	205.06	0.1548	1.8079
0.579	0.1545	0.2226	0.2593	0	17.846	193.96	0.1915	2.4831
0.580	0.509	0.2173	0.2593	0	18.102	181.01	0.1767	1.2844
0.581	0.3546	0.2178	0.2592	0	17.935	239.67	0.1654	1.6406
0.582	0.1721	0.2078	0.2571	0	18.088	298.29	0.149	2.3534
0.583	0.1761	0.1985	0.2546	0	18.272	314.11	0.1498	2.3383
0.584	0.3349	0.1992	0.2521	0	18.098	292.98	0.1707	1.6958
0.585	0.2011	0.1702	0.246	0	18.824	338.62	0.1673	2.245
0.586	0.1877	0.1565	0.2405	0	19.191	401.05	0.1727	2.2818
0.587	0.162	0.162	0.2424	0	19.205	462	0.1775	2.4122
0.588	0.0623	0.0958	0.241	0	21.478	584	0.1387	3.4071

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.589	0.3332	0.0898	0.2434	0	21.997	517.61	0.2017	1.8177
0.590	0.2926	0.0746	0.246	0	22.912	438.08	0.2234	1.833
0.591	0.3059	0.0626	0.2515	0	23.855	281.92	0.2217	1.8035
0.592	0.3108	0.0519	0.2546	0	24.284	248.81	0.226	1.7803
0.593	0.3	0.0294	0.2558	0	24.957	286.67	0.2296	1.8236
0.594	0.3222	-0.0066	0.2549	0	25.788	435.3	0.2172	1.7626
0.595	0.1237	-0.0156	0.2551	0	25.989	551.75	0.211	2.7115
0.596	0.3077	-0.0202	0.2553	0	25.926	609.18	0.1929	1.7805
0.597	0.31	-0.022	0.2565	0	26.015	539.07	0.186	1.778
0.598	0.3042	-0.0294	0.257	0	26.044	548.65	0.1478	1.7996
0.599	0.3088	-0.0353	0.2559	0	25.918	517.43	0.1121	1.7661
0.600	0.3	-0.0393	0.2551	0	25.955	469.34	0.0792	1.7996
0.601	0.3041	-0.0446	0.2545	0	25.975	489.79	0.0452	1.7768
0.602	0.2936	-0.0439	0.2545	0	25.949	539.1	0.0287	1.8262
0.603	0.304	-0.0294	0.255	0	25.358	742.02	0.0077	1.7522
0.604	0.2992	-0.0336	0.2544	0	25.343	991.67	-0.0563	1.7715
0.605	0.3094	-0.0385	0.2536	0	25.452	1024.9	-0.1006	1.742
0.606	0.304	-0.0442	0.252	0	25.463	1120.2	-0.2281	1.7554
0.607	0.2814	-0.0458	0.2509	0	25.46	1072.6	-0.3347	1.8294
0.608	0.3099	-0.0386	0.2515	0	25.183	1020.8	-0.5578	1.7363
0.609	0.3033	-0.0432	0.251	0	25.368	976.6	-1.9358	1.7488
0.610	0.1801	-0.0172	0.2526	0	24.491	912.46	0	2.3025
0.611	0.1635	-0.0092	0.2536	0	24.502	639.48	0	2.3694
0.612	0.1752	-0.0104	0.2534	0	24.838	517.17	0	2.3184
0.613	0.3317	-0.0056	0.2533	0	24.895	598.58	0	1.6873
0.614	0.3042	-0.0115	0.2528	0	25.446	669.72	0	1.7504

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.615	0.1719	-0.0115	0.2533	0	25.761	672.45	0	2.3172
0.616	0.3319	-0.0129	0.2539	0	26.263	567.54	0	1.7191
0.617	0.3198	-0.0113	0.2551	0	26.607	601.23	0	1.6984
0.618	0.3884	-0.008	0.256	0	27.105	660.67	0	1.4951
0.619	0.2354	-0.0052	0.2562	0	27.356	648.99	0	2.008
0.620	0.3106	-0.0038	0.2555	0	27.457	698.65	0	1.718
0.621	0.3056	-0.009	0.2543	0	27.967	830.22	0	1.7583
0.622	0.3493	-0.0101	0.253	0	28.174	982.08	0	1.609
0.623	0.3182	-0.0134	0.2517	0	28.832	1002	0	1.7233
0.624	0.3191	-0.0106	0.2525	0	29.16	1075.8	0	1.7243
0.625	0.2192	-0.0083	0.253	0	29.87	1049.3	0	2.1105
0.626	0.3515	-0.0084	0.2533	0	30.426	1107.1	0	1.5993
0.627	0.1623	-0.0137	0.2536	0	31.339	1085.8	0	2.3707
0.628	0.2837	-0.014	0.2546	0	32.039	1111.6	0	1.8104
0.629	0.952	-0.0147	0.2548	0	32.506	1178.6	0	0.6112
0.631	0.2318	-0.0153	0.2562	0	33.143	1164.9	0	2.0418
0.633	0.3275	-0.0111	0.2587	0	33.497	1171.1	0	1.6835
0.635	0.2293	0.0026	0.2633	0	33.675	1035.4	0	2.0315
0.637	0.2258	0.0181	0.2678	0	34.18	728.63	0	2.0371
0.639	0.3021	0.0237	0.2718	0	35.129	479.86	0	1.7323
0.641	0.5151	0.0182	0.2733	0	37.021	93.986	0	1.2048
0.643	0.3202	0.0114	0.2742	0	39.287	-293.97	0	1.6641
0.645	0.2944	-0.042	0.2676	0	43.635	-282.6	0	1.7368
0.647	0.2102	-0.096	0.2607	0	47.847	-103.24	0	2.0848
0.649	0.3204	-0.1217	0.2575	0	49.897	227.16	0	1.699
0.651	0.3219	-0.1335	0.2521	0	50.057	949.78	0	1.6835

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.653	0.3089	-0.1427	0.242	0	49.12	2169.3	0	1.7348
0.655	0.3141	-0.1771	0.2288	0	49.578	3504.3	0	1.7511
0.657	0.3274	-0.1569	0.2342	0	49.799	3545.5	0	1.8144
0.659	0.294	-0.1298	0.2411	0	50.403	3247.6	0	1.8282
0.661	0.3576	-0.1315	0.2383	0	51.204	3807	0	1.6386
0.663	0.1711	-0.0978	0.2452	0	52.252	3241.7	0	2.3718
0.665	0.5232	-0.0498	0.2613	0	53.752	2093.2	0	1.2217
0.667	0.2983	-0.0374	0.2719	0	59.256	425.39	0	1.764
0.669	0.2635	45.033	0.2778	-4806.1	63.812	-812.47	1.6434	1.8574
0.671	0.1762	45.654	0.2832	-2005.6	66.136	-1288.6	1.2481	2.269
0.673	0.3002	0.7174	0.2828	-19.921	66.921	-729.57	0.3563	1.7336
0.675	0.3213	-1.3891	0.2694	27.465	68.846	783.53	-0.5904	1.678
0.677	0.2364	45.332	0.2578	-721.19	71.421	2699.8	-1.2343	1.998
0.679	0.3119	0.8925	0.2445	-13.245	77.53	4158.2	-1.5902	1.7314
0.681	0.3072	0.9867	0.2347	-12.708	83.505	5231.8	-1.7005	1.7497
0.683	0.3666	45.124	0.2264	-439.23	89.528	5942.2	-1.5926	1.5709
0.685	0.2985	1.0106	0.215	-10.433	99.596	6989.8	-1.9789	1.7421
0.687	0.3072	-0.8206	0.2119	4.8785	104.13	8083.8	-1.4628	1.6894
0.689	0.1019	-1.0855	0.2329	6.7636	109.59	5972.2	-0.9555	2.7964
0.691	0.2551	-0.5979	0.239	3.25	119.22	6034.5	-0.409	1.9216
0.693	0.2956	45.245	0.23	-356.39	129.15	7635.1	0.0016	1.8071
0.695	0.4218	6.4971	0.2292	-59.607	137.28	7224.7	0.1173	1.4662
0.697	0.3379	8.0348	0.2262	-84.76	146.23	7352.3	-0.002	1.6952
0.699	0.332	0.9691	0.2157	-15.015	157.5	8489.5	0.0836	1.7025
0.701	0.3241	-0.3675	0.291	2.7456	177.04	0	-0.7349	1.7182
0.703	0.2941	-1.1362	0.2867	17.778	188.11	0	-0.7999	1.8116

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.705	1.8856	-24.192	0.2867	639.41	198.06	0	-0.9947	-0.0707
0.707	0.6966	-45.762	0.2881	2025.8	199.97	0	-1.2051	0.9262
0.709	0.3043	-0.9458	0.2923	109.28	196.78	0	-1.2346	1.7508
0.711	0.2728	0.0693	0.3135	0	160.15	0	-0.0531	1.8376
0.713	0.4461	0.1864	0.3251	0	140.51	0	-0.0097	1.3504
0.715	0.2494	0.1495	0.3215	0	165.49	0	-0.0013	1.9193
0.717	0.2977	0.0311	0.3275	0	220.01	0	0.0061	1.7542
0.719	0.2861	-0.0116	0.3144	0	248.09	0	0.0167	1.856
0.721	0.3589	0.0303	0.3097	0	247.72	0	0.0187	1.646
0.723	0.3345	-0.0326	0.3229	0	289.18	0	0.0128	1.6983
0.725	0.3624	-0.014	0.3246	0	303.68	0	0.013	1.6206
0.727	0.323	0.0061	0.3266	0	303.52	0	0.0179	1.7525
0.729	0.3929	-0.0266	0.3252	0	318.45	0	0.0204	1.5768
0.731	0.4718	-0.0571	0.308	0	324.7	0	0.0226	1.3846
0.733	0.2827	-0.0584	0.2972	0	321.28	0	0.0187	1.8854
0.735	0.2816	-0.0714	0.2993	0	328.55	0	0.011	1.874
0.737	0.2612	-0.0865	0.2898	0	337.45	0	0.0039	1.9292
0.739	0.2196	-0.0905	0.2896	0	341.93	0	-0.0171	2.1001
0.741	0.1629	-0.1036	0.2855	0	351.63	0	-0.1563	2.3988
0.743	0.1493	-0.1018	0.2827	0	357.93	0	-0.2565	2.4532
0.745	0.2807	-0.1216	0.28	0	377.15	0	-0.4369	1.8176
0.747	0.5543	-0.1111	0.2782	0	384.79	0	-0.6286	1.1286
0.749	0.2166	-0.1127	0.2789	0	398.98	0	-0.932	2.0741
0.751	0.2818	-0.107	0.2784	0	411.29	0	-2.1165	1.8126
0.753	0.1407	-0.0963	0.2787	0	422.73	0	-20.948	2.5074
0.755	0.3607	-0.092	0.2745	0	444.02	0	-34.186	1.5615

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.757	0.292	-0.115	0.2558	0	502.2	0	-240.47	1.6159
0.759	0.2461	0.7209	0.2838	-0.6315	529.58	0	-535.43	1.6537
0.761	0.2475	-0.5423	0.2836	0.2201	555.96	0	-1196.3	1.5549
0.763	0.4035	0.5601	0.324	-0.1051	518.76	0	0	1.183
0.765	0.3338	-0.7954	0.3148	0.3835	590.58	0	0	1.4954
0.767	0.2897	-1.1583	0.306	1.5626	648.83	0	0	1.7614
0.769	0.2973	-1.0155	0.2966	2.93	793.27	0	-189.7	1.743
0.771	0.271	1.0944	0.2895	-4.8093	959.87	0	-99.448	1.8457
0.773	0.2951	0.98	0.2846	-5.5655	1215.7	0	-62.298	1.7587
0.775	0.3634	-0.9609	0.2818	6.1116	1685.9	0	-44.535	1.5678
0.777	0.294	-0.98	0.2833	10.586	2756.5	0	-35.498	1.7689
0.779	0.6301	19.674	0.2826	-706.49	8416.8	0	-31.765	1.0075
0.781	0.3014	0.6793	0.3516	0	0	0	0.801	1.7529
0.783	0.2856	0.6829	0.3512	0	0	0	0.6256	1.8205
0.785	0.4559	0.6963	0.3398	0	0	0	0.5778	1.3585
0.787	0.2841	0.7133	0.337	0	0	0	0.4476	1.8311
0.789	0.2819	0.722	0.341	0	0	0	0.7142	1.8535
0.791	0.1314	0.7158	0.3506	0	0	0	0.5601	2.6079
0.793	0.2805	0.7111	0.3632	0	0	0	0.4934	1.8541
0.795	0.3377	0.7082	0.375	0	0	0	0.5203	1.6803
0.797	0.2993	0.7107	0.377	0	0	0	0.5746	1.7977
0.799	0.3158	0.7144	0.3808	0	0	0	0.6036	1.7619
0.801	0.3283	0.7181	0.3827	0	0	0	0.1691	1.7184
0.803	0.2863	0.7144	0.3805	0	0	0	0.072	1.8641
0.805	0.2435	0.7078	0.3752	0	0	0	0.0406	2.0212
0.807	0.1961	0.7091	0.3702	0	0	0	0.0308	2.23
0.809	0.2489	0.7232	0.3681	0	0	0	0.0278	2.0095

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.811	0.2368	0.7506	0.3714	0	0	0	0.0346	2.0545
0.813	0.3056	0.7907	0.3967	0	0	0	0.0381	1.7893
0.815	0.2803	0.8159	0.4012	0	0	0	0.0415	1.8682
0.817	0.2991	0.8117	0.4066	0	0	0	0.0409	1.8094
0.819	0.2483	0.7957	0.397	0	0	0	0.0325	2.0142
0.821	0.3175	0.7918	0.4061	0	0	0	0.0275	1.7441
0.823	0.1423	0.7811	0.4092	0	0	0	0.023	2.5519
0.825	0.2699	0.7724	0.3934	0	0	0	0.0243	1.9084
0.826	0.3031	0.7696	0.4002	0	0	0	0.0264	1.7864
0.828	0.2766	0.7689	0.4008	0	0	0	0.0327	1.8668
0.830	0.3915	0.7635	0.4014	0	0	0	0.0512	1.529
0.832	0.1841	0.7516	0.4046	0	0	0	0.0755	2.2843
0.834	0.0977	0.7358	0.3938	0	0	0	0.0887	2.9249
0.836	0.2942	0.7227	0.3944	0	0	0	0.0969	1.8162
0.838	0.0752	0.7124	0.392	0	0	0	0.0935	3.1712
0.840	0.289	0.7035	0.3848	0	0	0	0.1037	1.8186
0.842	0.2831	0.6953	0.3807	0	0	0	0.1061	1.8312
0.844	0.2831	0.6886	0.3801	0	0	0	0.095	1.833
0.846	0.2964	0.6841	0.3777	0	0	0	0.0645	1.7593
0.848	0.2809	0.6835	0.3777	0	0	0	0.0584	1.7979
0.850	0.1678	0.685	0.3783	0	0	0	0.0407	2.343
0.852	0.2911	0.6845	0.3847	0	0	0	0.0757	1.7417
0.854	0.272	0.6817	0.3867	0	0	0	0.1053	1.9334
0.856	0.176	0.6768	0.3804	0	0	0	0.1862	2.2778
0.858	0.2585	0.6748	0.3855	0	0	0	0.1836	1.8705
0.860	0.3385	0.6737	0.3804	0	0	0	0.0473	1.6033
0.862	0.3399	0.6739	0.3763	0	0	0	-8.676	1.5854

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.864	0.296	0.6742	0.382	0	0	0	-4.0922	1.6946
0.866	0.1152	0.6727	0.3843	0	0	0	-4.4917	2.7367
0.868	0.1887	0.6708	0.3798	0	0	0	0.8322	2.2043
0.870	0.4262	0.6697	0.4005	0	0	0	-1.0307	1.3605
0.872	0.5982	0.6716	0.402	0	0	0	-2.1481	1.0106
0.874	0.2032	0.6715	0.4008	0	0	0	-1.3469	2.1017
0.876	0.242	0.6716	0.3997	0	0	0	-0.1909	1.9359
0.878	0.2256	0.6726	0.4016	0	0	0	0.2468	1.9936
0.880	0.1999	0.6744	0.4019	0	0	0	0.0094	2.1343
0.882	0.2938	0.6757	0.4008	0	0	0	0.0057	1.7577
0.884	0.3116	0.6778	0.4035	0	0	0	0.0053	1.6954
0.886	0.3025	0.6806	0.4046	0	0	0	0.0038	1.7458
0.888	0.1877	0.6837	0.3975	0	0	0	0.0039	2.2197
0.890	0.1637	0.6943	0.3992	0	0	0	0.0041	2.3459
0.892	0.3156	0.7192	0.4054	0	0	0	0.0066	1.7099
0.894	0.3748	0.7563	0.4151	0	0	0	0.0076	1.5155
0.896	0.2775	0.7965	0.4243	0	0	0	0.012	1.8246
0.898	0.2107	0.8249	0.4479	0	0	0	0.0132	2.0886
0.90	0.5208	0.8273	0.4626	0	0	0	0.0134	1.2231
0.902	0.2937	0.8028	0.4376	0	0	0	0.0117	1.8447
0.904	0.4679	0.8002	0.4365	0	0	0	0.0092	1.3295
0.906	0.5582	0.822	0.4608	0	0	0	0.0091	1.1492
0.908	0.3112	0.8454	0.4594	0	0	0	0.0114	1.7519
0.910	0.0911	0.8581	0.4543	0	0	0	0.0143	3.0119
0.912	0.1995	0.8717	0.4756	0	0	0	0.016	2.2275
0.914	0.3914	0.8833	0.4888	0	0	0	0.0182	1.5541
0.916	0.3011	0.8698	0.4834	0	0	0	0.0201	1.8493

wavelength	Coefficients							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.918	0.2832	0.8358	0.4666	0	0	0	0.0169	1.8839
0.920	0.2314	0.8104	0.4548	0	0	0	0.0144	2.0672
0.922	0.2065	0.8139	0.4541	0	0	0	0.0136	2.2088
0.924	0.2025	0.8355	0.447	0	0	0	0.0152	2.2495
0.926	0.2792	0.885	0.4288	0	0	0	0.0088	1.8793
0.928	0.0136	0.9617	0.4548	0	0	0	0.0065	4.8791
0.930	0.019	1.078	0.4517	0	0	0	0.0053	4.4302
0.932	0.0233	1.2	0.4694	0	0	0	0.0062	4.2629
0.934	0.0217	1.2864	0.4908	0	0	0	0.0062	4.3796
0.936	0.024	1.2658	0.5196	0	0	0	0.0056	4.3789
0.938	0.0166	1.1951	0.475	0	0	0	0.005	4.8074
0.940	0.0223	1.1922	0.4946	0	0	0	0.0046	4.5332
0.942	0.034	1.2035	0.4961	0	0	0	0.0045	4.0794
0.944	0.0189	1.2077	0.4821	0	0	0	0.005	4.6532
0.946	0.0188	1.1881	0.4769	0	0	0	0.0051	4.6197
0.948	0.0211	1.1768	0.491	0	0	0	0.0052	4.5084
0.950	0.025	1.1707	0.5007	0	0	0	0.0058	4.3809

Appendix 4

The value of the model coefficients for all-sky

The value of the model coefficients for every 0.001 µm of the model for calculating global spectral irradiance under all-sky conditions.

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.350	-15.989	0.166	-1.064	-9.849	164.469
0.351	-8.903	0.155	-1.060	17.577	28.074
0.352	-8.600	0.174	-1.077	4.600	62.097
0.353	-25.887	0.159	-1.048	41.137	96.887
0.354	8.239	0.129	-1.008	-1.518	-55.752
0.355	5.519	0.109	-0.986	10.484	-67.568
0.356	7.530	0.112	-0.990	-21.696	7.247
0.357	91.583	0.113	-1.006	-311.224	158.925
0.358	24.015	0.115	-1.005	-47.904	-47.933
0.359	-7.797	0.114	-1.001	3.571	56.086
0.360	-6.530	0.055	-0.926	-3.276	64.973
0.361	26.673	0.063	-0.958	-34.844	-102.616
0.362	3.665	0.075	-0.967	-54.126	126.960
0.363	25.012	0.102	-1.016	-43.860	-63.564
0.364	0.732	0.095	-1.024	20.953	-57.598
0.365	4.799	0.053	-0.927	-60.040	133.788
0.366	1.031	0.028	-0.892	-21.176	55.523
0.367	-3.239	0.026	-0.889	-39.101	135.918
0.368	12.981	0.009	-0.862	12.121	-123.475
0.369	-1.456	0.004	-0.864	23.287	-47.098
0.370	26.455	-0.032	-0.814	-29.127	-109.137
0.371	12.054	-0.027	-0.823	-30.522	0.077
0.372	-24.222	-0.074	-0.729	20.503	125.163

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.373	-1.485	-0.059	-0.770	-17.095	61.796
0.374	-10.942	-0.015	-0.848	29.627	4.246
0.375	6.663	-0.003	-0.837	6.257	-59.030
0.376	6.422	-0.017	-0.826	7.137	-59.368
0.377	14.002	-0.007	-0.853	-49.475	37.772
0.378	17.933	-0.044	-0.782	-43.038	-6.648
0.379	15.424	-0.080	-0.732	-0.004	-102.321
0.380	42.595	-0.159	-0.561	-131.628	56.528
0.381	4.716	-0.154	-0.573	-22.668	32.073
0.382	-0.688	-0.171	-0.506	-18.108	57.084
0.383	4.141	-0.131	-0.618	-58.403	129.150
0.384	-1.308	-0.105	-0.658	22.362	-44.509
0.385	-3.766	-0.083	-0.715	-11.946	61.211
0.386	13.953	-0.090	-0.649	-34.810	1.248
0.387	-7.844	-0.058	-0.722	19.145	7.630
0.388	-6.106	-0.067	-0.682	-46.072	163.874
0.389	2.021	-0.100	-0.643	17.761	-54.379
0.390	-18.189	-0.149	-0.566	43.965	11.491
0.391	4.132	-0.177	-0.538	-22.791	36.014
0.392	-5.295	-0.187	-0.505	-7.643	58.627
0.393	3.332	-0.192	-0.502	15.217	-55.621
0.394	-2.598	-0.179	-0.525	22.779	-36.451
0.395	7.229	-0.128	-0.614	4.076	-52.053
0.396	3.691	-0.103	-0.619	14.272	-55.200
0.397	2.208	-0.026	-0.805	17.156	-52.757
0.398	5.636	-0.031	-0.788	9.390	-54.745
0.399	-20.802	-0.078	-0.670	8.841	112.796

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.400	2.984	-0.074	-0.707	15.633	-53.333
0.401	-13.729	-0.096	-0.658	-31.396	168.028
0.402	9.319	-0.136	-0.610	-8.150	-32.999
0.403	-7.328	-0.165	-0.559	-0.100	49.787
0.404	19.320	-0.179	-0.534	-14.750	-77.447
0.405	4.894	-0.171	-0.550	11.317	-53.382
0.406	28.807	-0.160	-0.569	-37.502	-78.025
0.407	-3.305	-0.161	-0.555	28.086	-44.707
0.408	-0.081	-0.138	-0.609	20.041	-44.309
0.409	-8.453	-0.142	-0.583	17.258	12.589
0.410	-2.174	-0.129	-0.614	21.799	-35.984
0.411	5.096	-0.126	-0.628	30.031	-99.017
0.412	19.170	-0.138	-0.593	-4.680	-97.397
0.413	8.211	-0.145	-0.586	-0.148	-43.610
0.414	5.770	-0.155	-0.558	-20.990	21.180
0.415	-4.728	-0.155	-0.577	49.082	-86.692
0.416	-8.715	-0.174	-0.535	10.831	28.436
0.417	0.113	-0.177	-0.543	-17.957	46.511
0.418	-0.649	-0.177	-0.534	22.408	-45.813
0.419	-1.022	-0.181	-0.526	20.698	-39.527
0.420	-4.923	-0.185	-0.523	-8.448	52.063
0.421	8.143	-0.188	-0.518	0.339	-42.725
0.422	12.373	-0.196	-0.508	-14.535	-31.011
0.423	7.992	-0.198	-0.492	-45.035	65.793
0.424	-1.557	-0.189	-0.529	-15.367	48.881
0.425	2.197	-0.195	-0.513	16.299	-46.535
0.426	-4.312	-0.203	-0.492	-9.908	50.962

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.427	-3.646	-0.209	-0.478	-11.403	50.617
0.428	6.854	-0.209	-0.492	5.483	-46.266
0.429	3.667	-0.184	-0.536	13.561	-47.627
0.430	-6.553	-0.161	-0.573	238.392	-515.108
0.431	-2.877	-0.121	-0.647	21.272	-30.010
0.432	-21.112	-0.106	-0.680	-105.250	360.571
0.433	3.965	-0.108	-0.650	12.849	-47.070
0.434	0.622	-0.089	-0.702	-17.977	41.886
0.435	4.637	-0.106	-0.668	11.393	-46.944
0.436	22.841	-0.122	-0.630	-0.334	-115.651
0.437	7.252	-0.113	-0.664	4.131	-43.698
0.438	8.448	-0.109	-0.660	-0.867	-38.345
0.439	26.704	-0.094	-0.691	-40.524	-42.549
0.440	-6.485	0.019	-0.839	-3.801	45.789
0.441	-8.660	0.015	-0.828	7.174	31.869
0.442	-18.661	0.027	-0.854	-81.769	284.125
0.443	-30.364	0.025	-0.862	54.320	35.711
0.444	-2.954	0.015	-0.833	-40.769	110.391
0.445	8.439	0.008	-0.828	-16.837	-0.987
0.446	3.986	0.007	-0.813	-50.178	96.047
0.447	1.499	0.007	-0.802	16.752	-41.628
0.448	-8.989	0.009	-0.812	13.672	17.810
0.449	3.115	0.002	-0.809	14.128	-43.407
0.450	-7.680	-0.010	-0.794	20.332	-3.740
0.451	-2.166	-0.029	-0.752	20.162	-30.549
0.452	-7.650	-0.034	-0.756	24.469	-13.181
0.453	2.237	-0.033	-0.772	15.475	-41.564

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.454	-4.781	-0.034	-0.773	-8.500	45.402
0.455	9.119	-0.031	-0.781	-4.481	-30.735
0.456	4.320	-0.034	-0.755	-19.579	25.611
0.457	5.020	-0.029	-0.788	10.234	-42.995
0.458	3.530	-0.027	-0.791	13.220	-42.264
0.459	3.150	-0.041	-0.749	14.876	-43.949
0.460	0.916	-0.030	-0.786	30.538	-67.322
0.461	4.477	-0.028	-0.798	-19.441	24.484
0.462	-6.968	-0.038	-0.763	56.744	-86.806
0.463	-0.446	-0.047	-0.745	-15.899	39.775
0.464	26.916	-0.044	-0.762	-36.070	-43.937
0.465	-9.503	-0.049	-0.754	16.882	10.975
0.466	1.604	-0.048	-0.764	16.055	-38.525
0.467	-17.081	-0.054	-0.734	2.087	77.156
0.468	8.707	-0.046	-0.760	-1.488	-33.281
0.469	15.217	-0.042	-0.764	-31.183	0.579
0.470	20.555	-0.039	-0.769	20.642	-133.709
0.471	-8.694	-0.038	-0.769	5.887	29.924
0.472	0.679	-0.034	-0.778	-16.903	35.989
0.473	-2.218	-0.038	-0.772	-13.200	41.030
0.474	8.703	-0.035	-0.782	-1.314	-32.762
0.475	4.629	-0.031	-0.798	10.848	-40.165
0.476	-23.324	-0.026	-0.808	22.084	59.732
0.477	6.607	-0.026	-0.800	6.194	-38.856
0.478	-14.412	-0.026	-0.801	31.109	1.151
0.479	3.296	-0.027	-0.798	13.232	-38.851
0.480	26.628	-0.018	-0.832	-36.394	-36.624

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.481	-1.048	-0.026	-0.812	-14.711	38.236
0.482	1.942	-0.029	-0.811	15.224	-36.816
0.483	-0.078	-0.062	-0.756	17.547	-32.874
0.484	3.293	-0.067	-0.743	19.786	-51.834
0.485	6.644	-0.073	-0.735	-19.783	15.644
0.486	8.713	-0.054	-0.756	-1.063	-31.621
0.487	9.178	-0.032	-0.807	-3.623	-28.197
0.488	2.361	-0.005	-0.863	14.501	-36.603
0.489	4.462	-0.018	-0.804	10.998	-38.136
0.490	-2.275	-0.006	-0.854	-12.811	38.624
0.491	-4.628	-0.012	-0.842	-8.573	39.646
0.492	-0.703	-0.016	-0.832	18.061	-30.824
0.493	-1.839	-0.020	-0.824	18.643	-27.285
0.494	7.090	-0.015	-0.836	5.777	-37.787
0.495	4.070	-0.017	-0.832	-18.358	23.425
0.496	-1.286	-0.017	-0.832	18.197	-28.522
0.497	-5.944	-0.018	-0.838	-5.507	38.069
0.498	9.747	-0.027	-0.812	-11.001	-14.302
0.499	-1.574	-0.028	-0.812	-13.657	36.599
0.500	3.696	-0.028	-0.813	12.225	-36.341
0.501	-2.737	-0.025	-0.828	18.881	-23.879
0.502	26.760	-0.012	-0.835	-16.440	-70.573
0.503	8.412	-0.003	-0.841	-16.514	2.432
0.504	10.083	0.008	-0.870	-8.652	-19.697
0.505	-0.789	0.018	-0.886	17.579	-28.903
0.506	8.900	0.021	-0.890	-1.497	-29.004
0.507	4.530	0.017	-0.879	-18.130	20.923

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.508	8.539	0.017	-0.868	0.134	-30.576
0.509	-2.354	0.019	-0.884	18.479	-24.453
0.510	9.194	0.005	-0.862	-2.938	-26.833
0.511	2.102	-0.002	-0.852	-17.063	28.091
0.512	-7.850	-0.010	-0.842	0.192	32.313
0.513	-2.702	-0.020	-0.842	18.535	-23.124
0.514	-8.209	-0.033	-0.814	1.627	30.649
0.515	7.625	-0.039	-0.804	3.414	-32.652
0.516	-4.104	-0.056	-0.780	-9.418	36.397
0.517	6.455	-0.044	-0.791	6.585	-34.175
0.518	-1.097	-0.026	-0.832	-13.932	33.685
0.519	-8.803	-0.010	-0.840	14.030	8.321
0.520	-0.014	0.006	-0.886	-15.104	31.758
0.521	9.171	-0.003	-0.863	-13.721	-4.798
0.522	-4.768	0.011	-0.891	-8.118	35.679
0.523	2.113	-0.002	-0.860	14.170	-32.195
0.524	6.654	-0.009	-0.856	6.077	-33.208
0.525	2.734	-0.018	-0.820	13.310	-32.664
0.526	-6.830	-0.002	-0.798	-3.353	33.500
0.527	0.408	0.010	-0.843	-15.401	30.246
0.528	9.441	0.010	-0.850	-3.849	-24.079
0.529	-4.518	0.007	-0.847	18.498	-16.333
0.530	8.736	0.012	-0.863	0.537	-29.610
0.531	-6.440	0.002	-0.851	19.535	-11.437
0.532	2.878	-0.019	-0.808	12.985	-32.088
0.533	-3.311	0.002	-0.854	-10.645	34.130
0.534	-1.303	0.025	-0.905	-13.429	32.226

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.535	3.386	0.026	-0.906	12.225	-32.184
0.536	5.082	0.028	-0.912	-17.481	17.414
0.537	5.807	0.024	-0.903	7.957	-32.476
0.538	-0.761	0.023	-0.900	16.780	-26.088
0.539	9.969	0.020	-0.899	-10.279	-12.774
0.540	-1.569	0.022	-0.904	17.289	-24.175
0.541	1.655	0.023	-0.898	-16.102	26.558
0.542	2.871	0.032	-0.926	-16.795	23.650
0.543	8.076	0.035	-0.931	2.292	-29.184
0.544	-7.640	0.029	-0.913	-1.078	30.217
0.545	9.892	0.033	-0.929	-9.780	-12.951
0.546	5.902	0.032	-0.927	7.732	-31.560
0.547	8.052	0.033	-0.929	2.416	-28.934
0.548	-3.557	0.037	-0.933	17.955	-18.535
0.549	8.100	0.038	-0.935	2.290	-28.672
0.550	7.880	0.040	-0.936	2.955	-29.057
0.551	-7.096	0.041	-0.937	-2.781	30.773
0.552	-2.885	0.042	-0.939	-11.099	31.921
0.553	8.572	0.041	-0.935	0.802	-27.144
0.554	3.172	0.043	-0.945	-16.685	22.110
0.555	1.267	0.037	-0.927	14.606	-28.114
0.556	-6.958	0.032	-0.921	-3.191	30.566
0.557	1.206	0.035	-0.923	-15.473	26.201
0.558	-3.147	0.037	-0.925	-10.661	31.508
0.559	-9.287	0.043	-0.945	6.082	21.127
0.560	0.887	0.041	-0.935	14.914	-27.187
0.561	24.328	0.045	-0.944	-34.399	-13.718

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.562	-9.527	0.042	-0.940	10.391	13.928
0.563	-9.214	0.040	-0.936	14.343	5.844
0.564	-7.996	0.042	-0.940	-0.249	27.821
0.565	-1.968	0.034	-0.928	-12.193	29.984
0.566	9.335	0.032	-0.926	-1.931	-23.496
0.567	-4.561	0.033	-0.928	-9.904	33.877
0.568	7.870	0.018	-0.902	5.059	-31.075
0.569	-1.607	0.024	-0.923	-12.582	29.289
0.570	-4.155	0.007	-0.908	17.604	-15.841
0.571	-3.461	0.015	-0.924	18.432	-19.423
0.572	-18.595	0.016	-0.934	28.669	8.950
0.573	-2.313	0.015	-0.929	-11.652	29.607
0.574	-8.566	0.014	-0.927	14.603	2.777
0.575	3.406	0.009	-0.916	11.752	-28.528
0.576	9.139	0.001	-0.890	0.041	-25.413
0.577	9.730	0.012	-0.920	-12.576	-5.232
0.578	-4.366	0.016	-0.924	-8.603	30.139
0.579	-9.414	0.023	-0.935	6.019	19.866
0.580	26.071	0.027	-0.937	-34.026	-16.666
0.581	10.808	0.026	-0.934	-7.974	-16.136
0.582	6.374	0.026	-0.948	7.865	-30.177
0.583	25.735	0.020	-0.938	-36.240	-11.395
0.584	-1.688	0.017	-0.930	-12.293	28.156
0.585	-4.102	-0.011	-0.874	18.103	-16.813
0.586	8.080	-0.032	-0.854	2.822	-26.163
0.587	9.320	-0.034	-0.874	-1.223	-22.775
0.588	-5.182	-0.103	-0.746	-7.144	29.291

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.589	-1.459	-0.109	-0.732	16.280	-21.262
0.590	-7.064	-0.100	-0.762	-3.182	27.846
0.591	8.157	-0.103	-0.762	2.667	-25.720
0.592	22.317	-0.092	-0.782	-44.227	13.163
0.593	-2.374	-0.085	-0.793	16.670	-19.238
0.594	-8.498	-0.078	-0.799	0.932	24.635
0.595	-7.468	-0.072	-0.805	16.078	-3.823
0.596	6.455	-0.069	-0.811	6.681	-27.284
0.597	3.033	-0.055	-0.818	12.033	-26.575
0.598	6.045	-0.047	-0.837	7.938	-28.107
0.599	-2.021	-0.044	-0.840	16.397	-19.676
0.600	-2.945	-0.033	-0.852	-10.584	27.880
0.601	-10.225	-0.026	-0.861	11.979	10.422
0.602	-26.939	-0.021	-0.862	33.070	21.439
0.603	1.749	-0.015	-0.879	13.432	-25.051
0.604	-5.671	-0.020	-0.867	-6.265	27.943
0.605	-7.261	-0.019	-0.867	-2.863	26.590
0.606	6.782	-0.027	-0.853	5.989	-26.337
0.607	2.039	-0.026	-0.855	-15.180	21.486
0.608	2.641	-0.021	-0.871	-15.479	20.318
0.609	-8.049	-0.020	-0.871	15.286	-1.404
0.610	0.507	0.002	-0.866	-14.112	23.700
0.611	4.247	0.004	-0.872	-16.007	16.744
0.612	9.034	0.003	-0.866	-13.877	0.465
0.613	6.648	-0.002	-0.863	6.251	-25.979
0.614	-2.456	0.002	-0.870	16.330	-18.177
0.615	10.945	0.005	-0.871	-11.637	-8.119

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.616	9.537	0.005	-0.876	-12.908	-2.289
0.617	-7.188	0.009	-0.882	17.796	-8.082
0.618	10.880	0.009	-0.884	-10.462	-9.683
0.619	8.903	0.007	-0.879	-14.047	1.326
0.620	-6.108	0.007	-0.890	-5.505	26.633
0.621	10.008	0.002	-0.873	-12.087	-4.629
0.622	-9.906	-0.006	-0.858	12.622	7.164
0.623	9.214	-0.003	-0.862	-0.058	-21.794
0.624	8.965	-0.003	-0.864	0.758	-22.394
0.625	10.460	-0.015	-0.842	-7.775	-12.500
0.626	2.507	-0.013	-0.857	13.500	-26.127
0.627	2.622	-0.010	-0.865	-16.343	21.228
0.628	5.143	-0.012	-0.864	-15.873	14.061
0.629	10.429	-0.016	-0.858	-10.689	-7.544
0.631	7.827	-0.009	-0.877	4.102	-24.348
0.633	-9.975	-0.006	-0.879	8.796	12.793
0.635	3.525	0.005	-0.895	11.079	-24.410
0.637	-3.413	0.014	-0.892	-9.780	25.530
0.639	-5.559	0.029	-0.923	-6.569	25.642
0.641	-5.874	0.038	-0.930	16.333	-9.451
0.643	-3.229	0.036	-0.918	-9.998	25.075
0.645	11.325	0.019	-0.893	-8.036	-13.042
0.647	-0.548	-0.007	-0.875	14.811	-19.858
0.649	-1.863	-0.021	-0.861	-11.525	23.896
0.651	2.535	-0.039	-0.842	12.796	-23.933
0.653	-8.120	-0.088	-0.749	-1.351	22.805
0.655	-0.517	-0.104	-0.722	-12.756	22.385

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.657	-0.836	-0.084	-0.758	-12.461	22.583
0.659	0.084	-0.057	-0.811	-13.268	21.610
0.661	3.895	-0.070	-0.757	11.116	-24.080
0.663	-2.269	-0.038	-0.815	-11.003	23.398
0.665	5.148	0.002	-0.876	8.779	-23.224
0.667	5.421	0.035	-0.921	-15.401	12.503
0.669	-10.253	0.048	-0.955	8.224	12.244
0.671	8.433	0.052	-0.947	2.879	-21.407
0.673	-10.041	0.032	-0.917	12.590	5.070
0.675	5.723	0.001	-0.899	-15.302	11.715
0.677	-30.661	-0.052	-0.826	18.002	41.916
0.679	10.364	-0.088	-0.776	-2.901	-16.595
0.681	-0.310	-0.117	-0.750	14.277	-18.685
0.683	-2.735	-0.135	-0.722	-10.370	22.654
0.685	-4.257	-0.194	-0.613	-21.374	41.873
0.687	6.397	-0.183	-0.647	6.938	-22.039
0.689	-7.766	-0.130	-0.777	-2.641	21.785
0.691	5.271	-0.154	-0.732	8.615	-21.924
0.693	-5.318	-0.169	-0.724	-22.794	45.555
0.695	2.966	-0.160	-0.719	11.382	-20.945
0.697	7.138	-0.167	-0.703	5.755	-21.387
0.699	1.150	-0.184	-0.655	13.043	-19.442
0.701	-4.864	-0.110	-0.780	-7.704	22.410
0.703	29.264	-0.106	-0.767	-30.003	-15.030
0.705	-6.082	-0.091	-0.781	-5.907	22.106
0.707	5.168	-0.325	0.230	-14.979	12.324
0.709	0.623	-0.073	-0.794	13.348	-18.605

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.711	-11.291	-0.069	-0.805	8.066	12.414
0.713	7.523	-0.088	-0.786	-16.190	9.309
0.715	11.872	-0.171	-0.695	-8.632	-9.706
0.717	31.188	-0.245	-0.607	-13.809	-39.950
0.719	11.554	-0.182	-0.717	-10.682	-6.026
0.721	3.763	-0.128	-0.783	-14.567	14.384
0.723	0.460	-0.147	-0.773	13.570	-18.225
0.725	-6.077	-0.170	-0.732	-5.997	21.273
0.727	2.934	-0.151	-0.758	11.252	-19.606
0.729	-7.983	-0.123	-0.798	-2.848	20.333
0.731	-8.658	-0.043	-0.924	-1.271	19.335
0.733	11.448	-0.015	-0.903	-8.234	-8.718
0.735	-10.093	-0.018	-0.873	2.703	16.346
0.737	10.780	-0.002	-0.893	-2.585	-14.995
0.739	-10.866	0.020	-0.915	7.853	10.591
0.741	-15.770	0.043	-0.938	0.428	29.458
0.743	2.803	0.059	-0.944	11.280	-18.963
0.745	0.003	0.062	-0.932	-12.509	18.071
0.747	2.476	0.067	-0.930	11.565	-18.638
0.749	0.322	0.081	-0.959	-12.710	17.669
0.751	-0.986	0.072	-0.921	14.711	-16.573
0.753	-6.411	0.087	-0.950	15.174	-7.591
0.755	-10.538	0.083	-0.941	3.192	15.506
0.757	11.803	-0.093	-0.645	-7.280	-9.747
0.759	-8.054	-0.071	-0.749	-2.922	19.152
0.761	-9.573	-0.087	-0.749	0.404	17.299
0.763	9.641	0.126	-1.132	1.419	-17.199

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.765	5.041	0.165	-1.162	-14.908	12.040
0.767	5.151	0.195	-1.194	9.478	-19.925
0.769	-7.601	0.121	-1.033	-5.135	20.710
0.771	-9.268	0.098	-0.978	-0.623	17.590
0.773	-1.065	0.101	-0.977	-31.299	43.453
0.775	-27.110	0.104	-0.978	21.766	18.231
0.777	-7.365	0.102	-0.976	-7.946	23.599
0.779	12.042	0.093	-0.957	-4.508	-12.892
0.781	-0.336	-0.008	-0.834	-12.093	17.194
0.783	-13.351	-0.002	-0.846	18.250	-0.378
0.785	-15.755	-0.021	-0.811	0.411	26.194
0.787	8.927	-0.057	-0.776	3.263	-17.406
0.789	13.203	-0.050	-0.800	-13.569	-2.859
0.791	8.970	-0.058	-0.789	3.231	-17.282
0.793	6.150	-0.045	-0.797	8.042	-18.796
0.795	-7.400	-0.030	-0.835	-4.493	18.480
0.797	11.871	-0.022	-0.863	-8.483	-6.930
0.799	-8.167	-0.021	-0.859	-3.267	17.987
0.801	10.761	-0.023	-0.848	-11.921	-0.783
0.803	-10.303	-0.003	-0.880	12.858	1.063
0.805	-6.817	-0.002	-0.871	-5.707	18.694
0.807	7.631	-0.007	-0.858	5.601	-17.574
0.809	-10.953	-0.050	-0.780	3.188	13.872
0.811	-6.479	-0.082	-0.751	-5.950	18.284
0.813	2.277	-0.152	-0.656	11.501	-16.508
0.815	0.032	-0.204	-0.630	-12.183	16.013
0.817	4.015	-0.152	-0.748	10.014	-17.177

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.819	10.590	-0.127	-0.769	0.280	-15.058
0.821	-0.821	-0.115	-0.791	-11.603	16.430
0.823	10.900	-0.098	-0.813	-0.401	-14.527
0.825	-33.015	-0.095	-0.792	28.465	15.051
0.826	-6.927	-0.096	-0.798	-5.448	17.797
0.828	0.274	-0.110	-0.774	12.857	-14.870
0.830	-7.376	-0.095	-0.795	-5.205	18.023
0.832	0.548	-0.084	-0.807	13.507	-15.993
0.834	10.368	-0.055	-0.843	-12.655	1.299
0.836	-31.881	-0.019	-0.881	37.692	1.546
0.838	-2.101	-0.027	-0.849	-10.967	17.082
0.840	-7.281	-0.014	-0.859	14.850	-6.358
0.842	-4.425	0.002	-0.867	-8.515	17.346
0.844	5.724	0.018	-0.888	8.220	-16.790
0.846	0.480	0.003	-0.850	-12.433	15.005
0.848	5.290	0.003	-0.846	8.700	-16.639
0.850	-2.752	-0.014	-0.817	-10.082	16.642
0.852	2.059	0.008	-0.860	12.103	-16.068
0.854	6.079	0.025	-0.892	8.122	-16.879
0.856	-1.175	0.029	-0.883	13.496	-13.217
0.858	-5.479	0.022	-0.871	15.269	-9.409
0.860	9.673	0.009	-0.841	-13.513	3.577
0.862	5.823	0.001	-0.819	-14.100	9.455
0.864	-1.078	0.013	-0.843	13.853	-13.654
0.866	12.416	0.004	-0.832	-2.124	-13.171
0.868	11.749	0.032	-0.872	-1.552	-12.887
0.870	12.332	0.024	-0.860	8.325	-24.950

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.872	-2.934	0.012	-0.840	15.096	-12.541
0.874	-5.908	0.018	-0.852	-8.201	18.026
0.876	-0.496	0.028	-0.865	13.089	-13.392
0.878	12.452	0.027	-0.869	-3.648	-11.096
0.880	-3.803	0.018	-0.856	14.324	-10.469
0.882	-2.650	0.028	-0.873	-10.178	15.841
0.884	-4.466	0.035	-0.885	-9.224	17.038
0.886	-1.823	0.030	-0.887	-10.806	15.409
0.888	5.761	0.020	-0.865	8.854	-16.391
0.890	7.030	-0.009	-0.816	-14.726	8.550
0.892	12.166	-0.047	-0.782	-0.278	-14.080
0.894	-10.243	-0.161	-0.617	-1.417	15.296
0.896	2.801	-0.166	-0.662	11.180	-15.040
0.898	-15.370	-0.201	-0.652	12.148	6.441
0.900	-12.619	-0.157	-0.768	7.214	8.469
0.902	8.349	-0.113	-0.834	6.043	-16.070
0.904	-13.233	-0.159	-0.715	7.268	9.021
0.906	-10.984	-0.192	-0.662	0.241	13.993
0.908	11.999	-0.240	-0.619	0.005	-13.659
0.910	-5.308	-0.218	-0.670	-7.834	15.909
0.912	-4.169	-0.247	-0.639	-8.919	15.679
0.914	1.652	-0.268	-0.624	-12.766	12.882
0.916	-2.524	-0.176	-0.791	-10.269	15.108
0.918	2.428	-0.162	-0.768	11.345	-14.391
0.920	-11.980	-0.145	-0.766	2.464	12.320
0.922	-10.115	-0.157	-0.743	-3.006	16.013
0.924	-12.883	-0.200	-0.658	6.639	8.753

wavelength	Coefficients				
	b_0	b_1	b_2	b_3	b_4
0.926	9.222	-0.389	-0.354	8.054	-18.594
0.928	2.329	-0.395	-0.304	11.326	-14.062
0.930	-5.207	-0.529	-0.159	-8.408	15.941
0.932	3.315	-0.236	-0.788	10.925	-14.633
0.934	6.782	-0.420	-0.517	7.526	-14.937
0.936	-8.008	-0.343	-0.762	-5.998	16.400
0.938	4.471	-0.335	-0.778	9.692	-14.576
0.940	7.260	-0.416	-0.601	-30.085	24.638
0.942	-12.870	-0.426	-0.559	4.845	10.223
0.944	11.024	-0.387	-0.636	2.765	-14.437
0.946	-2.585	-0.377	-0.686	24.778	-22.455
0.948	-1.028	-0.384	-0.645	-11.303	13.903
0.950	-8.950	-0.338	-0.711	14.102	-4.086

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VITA

NAME	Sunisa Khakhu
DATE OF BIRTH	11 May 1995
PLACE OF BIRTH	Surat Thani
INSTITUTIONS ATTENDED	2016, Bachelor of Science (Physics) Prince of Songkla University, Hat Yai, Thailand 2019, Master of Science (Physics) Silpakorn University, Nakhon Pathom, Thailand.
HOME ADDRESS	134 Moo 10, Bangngon, Phunphin, Surat Thani, 84130
PUBLICATION	Khakhu, S., Masiri, I., Wattan, R., & Janjai, S. (2023). A model for the estimation of global spectral solar irradiance under all-sky conditions for Nakhon Pathom station, Thailand. In Journal of Physics: Conference Series (Vol. 2431, No. 1, p. 012007). IOP Publishing. Khakhu, S., Masiri, I., Wattan, R., & Janjai, S. (2022). A semi-empirical model for calculating spectral global solar irradiance under clear sky conditions in Thailand. Journal of Renewable Energy and Smart Grid Technology, 17(2), 9-15. Sirikaew, S., Pattarapanitchai, S., Khakhu, S., & Janjai, S. (2022). A solar-powered vapor compression refrigeration system for vaccine storage. Journal of Renewable Energy and Smart Grid Technology, 17(2), 1-8. Sirikaew, S., Janjai, S., Khakhu, S., & Pattarapanitchai, S. (2022). Modification of a 220-V vapor compression refrigeration system to a 12-V photovoltaic solar-powered refrigeration system for cooling beverages: Modification process, performance, modeling, and economic evaluation. Science, Engineering and Health Studies, 22020010-22020010.