INTRODUCTION

The downwelling solar radiation received at the Earth surface is the major source of energy that is necessary for surface energy budget, land surface processes and all life activities of the ecosystem [1]. Also, it is considered as an essential parameter of surface and ecological models, such as Weather Research and Forecasting model (WRF) [2] the Community Land Model [3], general circulation models (GCMs) [4], engineering and other research purposes. Therefore, the general knowledge of solar radiation becomes necessary for a better understanding of the Earth and its climate system, in association with temporal and spatial changes of solar radiation.

There are different methods available for the measurements and estimation of solar radiation. Ground-based measurement by the use of an instrument like pyranometer or sun photometer is one of them. It is the most common method because of its added advantage of affordability over the other methods, and also a better and widely method used for calibration and validation purposes. However, the technique is low in terms of accuracy and spatial resolutions [6] [7]. Another common method is the satellite remote sensing method, which estimates the downward Total Solar Flux (TSF) more accurately with high spatial and temporal resolutions in the global scale of land and ocean. There are
In this work, we proposed the integration of the ground-based measurement and model simulation method of Discrete Ordinate Radiative Transfer (DISORT) model approach to estimate the downward TSF over Penang, Malaysia in a broadband shortwave range. Most of the empirical and semi-empirical models use data from satellite and remote sensing sources using the lookup table and other available techniques [12]. On the other hand, the radiative transfer method, which is based on the radiative transfer theory and the solution to the Radiative Transfer Equation (RTE), also requires inputs of the optical properties of aerosols and another additional variable, such as Solar Zenith Angle (SZA) and surface albedo. The ground-based measured parameters obtained from the Aerosol Robotic Network (AERONET) were used as inputs in this study. The discrete ordinate method has many advantages like the other available models; DISORT can be used as an alternative in the absence of downward data flux from other retrieval sources. Furthermore, it can be used as an excellent validation tool for the results of its kind.

2. Material and methods

In this work, we have estimated the downward TSF by considering the role aerosols play in the absence of cloud. The estimation was performed using “DISORT” radiative transfer codes in broadband of shortwave solar radiation, using the optical properties of aerosols (aerosol optical thickness, single scattering albedo and asymmetry factor of the selected days) retrieved from AERONET data. Other inputs used are surface albedo and the SZAs. The simulation has been performed on some two cloudless days, and the results were compared with the results of the resulting two cloud screened days obtained from AERONET measured using pyranometer.

The RTE for a plane-parallel homogeneous layer of atmosphere given by Chandrasekhar in 1960 [14] is:

$$\mu \frac{dI(\tau; \mu, \theta)}{d\tau} = I(\tau; \mu, \varphi, \psi) - J(\tau; \mu, \varphi, \psi)$$

where $I(\tau; \mu, \varphi, \psi)$ is the specific intensity at level $\tau$ along the direction $\mu$ and $\varphi$. The $\tau$ is the optical depth of a given layer or simply atmospheric aerosols optical depth (AOD) of that layer, $\varphi$ is the azimuthal angle, and $\mu$ is the direction of the solar intensity (upward or downward). The function,

$$J(\tau; \mu, \theta, \psi) = \frac{\omega}{4\pi} \int_{-1}^{1} \int_{0}^{2\pi} I(\tau; \mu', \varphi, \psi') P(\mu, \varphi; \mu', \varphi') d\mu' d\varphi'$$

$$+ \frac{\omega}{4\pi} F_\epsilon P(\mu, \varphi; -\mu_0, \varphi_0) e^{-\frac{\tau}{\mu_0}} + Q(\tau; \mu, \varphi, T)$$

is known as the source function, and the last term represents the internal source describing the thermal contribution of the Earth surface plus the scattering into the direction $\mu, \theta$ from all other directions, where $\omega$, is the single scattering albedo, and “P” is the scattering phase function. From the analytical
solution of DISORT, the general solution to RTE is the combination of homogeneous and particular solution for the total intensity. The equation for the broadband downward solar flux is obtained from the integral of that intensity as:

$$\mathbf{F}^\downarrow = \mu_0 F_0 e^{-\tau/\mu_0} + \int_0^{2\pi} d\varphi \int_0^1 \mu l(\tau, -\mu) d\tau = \mu_0 F_0 e^{-\tau/\mu_0} 2\pi \int_0^1 \mu l(\tau, -\mu) d\mu \quad (3)$$

where $F^\downarrow$ and $F_0$ are the instantaneous broadband solar flux at the surface of the Earth, and the initial solar flux at the top of the atmosphere respectively. The down sign indicates a downward direction and $\mu_0$ is the cosine of the SZA. It can be seen clearly from Equation (3) that the downward TSF ($F^\downarrow$) or the total energy crossing an area per unit time is obtained from the mean intensity.

2.1. Site Description and Instrument

Computations of broadband solar flux were performed to obtain the TSF of Universiti Sains Malaysia (USM), in Penang. Penang is an island located in the northwestern region of Peninsular Malaysia that lies within latitudes 5.20 to 5.50 ºN and longitudes 100.15 to 100.43 ºE [15]. This method can then be applied to estimate the DSF when the data from AERONET are not available. The optical properties of aerosols and the overpredicted TSF were examined using Sun photometer and solar energy measurement-pyranometer, respectively, which are all located at the rooftop of School of Physics, USM (longitude 100.30 ºE, latitude 5.36 ºN). Using the following user-defined inputs in the DISORT codes, the estimated results of the TSF were then obtained.

2.2 Input Data

To ensure excellent performance of the codes, attention has been given to the supplied input parameters. These inputs are very sensitive to the output results, by accommodating the optical and physical structure of the atmosphere, the response of the ground surface and to the SZA. The solar irradiance arrived at the top of the atmosphere has a value of about 1367 Wm$^{-2}$. There may be some small variations due to the difference in the precision of some methods [16]. In this work, 1367 Wm$^{-2}$ has been used, and this reduced to a particular value after passing through the atmosphere due to the interaction with aerosols, other constituents, and distance.

The optical properties of aerosols used in this work were obtained from AERONET data as measured by the sunphotometer. The sun photometer measures radiance at seven spectral range (340, 380, 440, 550, 670, 870, 1020nm) and the aerosols optical properties were also retrieved at all seven channels [15]. Therefore, as an input for the numerical estimation of broadband DSF, the daily average value for AOD at 550nm and SSA were used. However, not all solar radiation reaches the Earth’s surface; part of solar flux is being reflected into the atmosphere as a result of what is called surface albedo. It is defined as the ratio of solar energy reflected from the Earth to the incident radiation on its surface and is a crucial parameter in the regulation of the surface energy budget [17]. There had been a lot of estimates with regards to surface albedo over the years [18], but the average satellite record in the present day is 0.29 [19].

Note that, the effect of ozone in this work has been ignored due to the fact that the impact of ozone on downward shortwave irradiance at the surface of the Earth is minimal [20], and hence its transmission effect can be ignored. It has been observed that the effect in the variation of surface elevation below 1000m on shortwave radiation is insignificant [20], and thus the impact of surface elevation on Downward Solar Radiation (DSR) retrieval was not taken into account. A change of 1% occurs for an increase of 100m surface elevation, while a significant difference of 2.41% is observed for a variation of 6000 m elevation.
3. Results and discussions

The estimated and their corresponding measured TSF from AERONET values in a clear sky for the two days, 17/01/2015 and 01/02/2015 in Penang are shown in Figure 1 and 2. The two figures illustrate how the total downward flux changes with the change SZA in the interval of 15 mins Malaysian time (MYT).

To evaluate the general performance of the proposed integration of models and ground-based measurement to estimate the total solar flux of Penang for the stated periods, a statistical comparison was performed. The techniques used are: the correlation coefficient between the two results (r), the coefficient of determination ($R^2$), the root-mean-square error (RMSE) and the mean absolute percentage error (MAPE). The daily estimates of TSF using DISORT codes show good agreement with the ground-based measurement data from AERONET in the two days. Figure 3 shows the results of the comparison of the estimated against the measured in a scattered plot. These results are quite comparable to the
results obtained by (Wang and Piker) [21], with the correlation coefficient of 0.96 and mean absolute percentage error of 18% when they compare UMD/MODIS products and ground measurements. Some of the researches on TSF give more emphasis to parameters like the clearness index [22] and Link turbidity factor [23]. Whereas, in the DISORT model the key inputs are the aerosol parameters which provide a better opportunity to observe the impact of aerosols on the solar radiation.

However, from Figure 1 and 2, it can be observed that the TSF curves simulated using DISORT model provide an excellent estimation in comparison with the ground measurement curves. The points at which there is slight overestimation is at the maximum values of the total solar flux between 13 to 14 hours of the day. Nonetheless, the DISORT model predicts well the total solar flux in the first and the second half of the day. It is concluded that the DISORT model estimates the TSF to high level of accuracy. This would allow us to see the impact of atmospheric aerosols by using some arbitrary values of AOD at any selected SZA when the SSAs are maintained.

4. Conclusions

The proposed integration of the DISORT model that was based on the radiative transfer theory and the ground-based measurement from AERONET of the aerosol optical properties has been implemented. In this work, this method was used to estimate the TSF of Penang in Malaysia. The comparison between the DISORT model estimates and the measurement using Sun photometer shows a satisfactory correlation. The validation result shows that for the first day (r = 0.9968), (R² = 0.9936), root-mean-square error (RMSE) of 36.66 and mean absolute percentage error (MAPE) is 16%. For the second day (r = 0.9986), (R² = 0.9971), (RMSE = 33.06), (MAPE = 12%). The significance of this method is the inclusion of the aerosol optical properties and the SZA, which can provide an opportunity for further research on the effects of aerosol to the TSF. This method can also be used for predicting the TSF of a clear-sky atmosphere to serve as an alternative in the absence of results from AERONET and other retrieval sources.

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References

[1] S. Solomon and D. Qin, Climate Change 2007 The Physical Science Basis The, vol. 53, no. 9. 2013.
[2] W. C. Skamarock et al., “ARW Modelling System UserGuide V.3,” Book, no. January, p. 408, 2016.
[3] K. W. Oleson et al., “Technical description of version 4.0 of the Community Land Model (CLM),” NCAR/TN-478+STR NCAR Tech. Note, no. April, p. 266, 2010.
[4] X. Liang, D. P. Lettenmaier, E. F. Wood, and S. J. Burges, “A simple hydrologically based model of land surface water and energy fluxes for general circulation models,” J. Geophys. Res., vol. 99, no. D7, p. 14415, 1994.
[5] I. Laszlo, P. Ciren, H. Liu, S. Kondragunta, J. D. Tarpley, and M. D. Goldberg, “Remote sensing of aerosol and radiation from geostationary satellites,” Adv. Sp. Res., vol. 41, no. 11, pp. 1882–1893, 2008.
[6] D. Kim and V. Ramanathan, “Solar radiation budget and radiative forcing due to aerosols and clouds,” J. Geophys. Res. Atmos., vol. 113, no. 2, pp. 1–34, 2008.
[7] R. T. Pinker et al., “Surface Radiation Budgets in Support of the GEWEX Continental Scale International Project (GCIP) and the GEWEX Americas Prediction Project (GAPP), including the North American Land Data Assimilation System (NLDAS) Project Rachel,” J. Geophys. Res., no. 1, 2003.

[8] X. Zhang et al., “Local Adaptive Calibration of the Satellite-Derived Surface Incident Shortwave Radiation Product Using Smoothing Spline,” IEEE Trans. Geosci. Remote Sens., vol. 54, no. 2, pp. 1156–1169, 2016.

[9] B. Gschwind, L. Ménard, M. Albuisson, and L. Wald, “Converting a successful research project into a sustainable service: The case of the SoDa Web service,” Environ. Model. Softw., vol. 21, no. 11, pp. 1555–1561, 2006.

[10] L. Yang, X. Zhang, S. Liang, Y. Yao, K. Jia, and A. Jia, “Estimating Surface Downward Shortwave Radiation over China Based on the Gradient Boosting Decision Tree Method,” Remote Sens., 2018.

[11] A. K. Inamdar and P. C. Guillevic, “Net surface shortwave radiation from GOES imagery-product evaluation using ground-based measurements from SURFRAD,” Remote Sens., vol. 7, no. 8, pp. 10788–10814, 2015.

[12] Y. Ma and R. T. Pinker, “Modeling shortwave radiative fluxes from satellites,” J. Geophys. Res. Atmos., vol. 117, no. 23, pp. 1–19, 2012.

[13] K.-N. Liou, “Analytic two-stream and four-stream solutions for radiative transfer,” Journal of the Atmospheric Sciences, vol. 31, no. 5, pp. 1473–1475, 1974.

[14] S. Chandrasekhar, Radiative Transfer. 1960.

[15] X. Xia et al., “Aerosol optical properties and radiative effects in the Yangtze Delta region of China,” J. Geophys. Res., vol. 112, pp. 1–16, 2007.

[16] K. J. Li et al., “Why is the solar constant not a constant?,” Astrophys. J., vol. 747, no. 2, pp. 1–5, 2012.

[17] D.-X. S. Tao He, Shunlin Liang, “Analysis of global land surface albedo climatology and spatial-temporal variation during 1981–2010 from multiple satellite products,” J. Geophys. Res. Atmos., pp. 281–298, 2014.

[18] G. L. Stephens, D. O. Brien, P. J. Webster, P. Pilewski, S. Kato, and J. Li, “The albedo of Earth,” Rev. Geophys., pp. 1–23, 2015.

[19] C. Zender, Radiative Transfer in the Earth System Notes for Students of ESS 223 , Earth System Physics : Notes for Students of ESS 236 , Radiative Transfer and Remote Sensing : 2010.

[20] S. Liang, T. Zheng, R. Liu, H. Fang, and S. Tsay, “Estimation of incident photosynthetically active radiation from Moderate Resolution Imaging Spectrometer data,” J. Geophys. Res., vol. 111, pp. 1–13, 2006.

[21] H. Wang and R. T. Pinker, “Shortwave radiative fluxes from MODIS: Model development and implementation,” J. Geophys. Res. Atmos., vol. 114, no. 20, pp. 1–17, 2009.

[22] H. Alsamamra, “An estimation of global solar radiation at ground level using clear-sky radiation in Hebron city, Palestine,” Int. J. Renew. Energy, vol. 8, no. 2, pp. 13–20, 2013.

[23] K. Talbi and S. Harrouni, “Modeling of solar radiation received at ground level using semi empirical models for short time scales,” Proc. 2016 8th Int. Conf. Model. Identif. Control. ICMIC 2016, no. 8, pp. 603–607, 2017.