IOP Conference Series: Earth and Environmental Science

Development of local atmospheric model for estimating solar irradiance in Peninsular Malaysia

To cite this article: E C Yeap *et al* 2014 *IOP Conf. Ser.: Earth Environ. Sci.* **18** 012103

IOP Conf. Series: Earth and Environmental Science **18** (2014) 012103 doi:10.1088/1755-1315/18/1/012103

Development of local atmospheric model for estimating solar irradiance in Peninsular Malaysia

E C Yeap[1,·], A M S Lau[1], I Busu[2], K D Kanniah[1], A W Rasib[1] and W H W Kadir[1]

[1]Faculty of Geoinformation and Real Estate, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[2]Fakulti Sains Bumi, Universiti Malaysia Kelantan Kampus Jeli, Karung Berkunci No.100, 17600 Jeli, Kelantan, Malaysia.

E-mail: ecyeap2@live.utm.my

Abstract. Incoming solar irradiance covers a wide range of wavelengths with different intensities which drives almost every biological and physical cycle on earth at a selective wavelength. Estimation of the intensities of each wavelength for the solar irradiance on the earth surface provides a better way to understand and predict the radiance energy. It requires that the atmospheric and geometric input and the availability of atmospheric parameter is always the main concern in estimating solar irradiance. In this study, a local static atmospheric model for Peninsular Malaysia was built to provide the atmospheric parameters in the estimation of solar irradiance. Ten years of monthly Atmospheric Infrared Sounder (AIRS) average data (water vapor, temperature, humidity and pressure profile) of the Peninsular Malaysia was used for the building of the atmospheric model and the atmospheric model were assessed based on the measured meteorological data with RMSE of 4.7% and 0.7k for both humidity and temperature respectively. The atmospheric model were applied on a well-established radiative transfer model namely SMARTS2. Some modifications are required in order to include the atmospheric model into the radiative transfer model. The solar irradiance results were then assessed with measured irradiance data and the results show that both the radiative transfer model and atmospheric model were reliable with RMSE value of 0.5Wm^{-2}. The atmospheric model was further validated based on the measured meteorological data (temperature and humidity) provided by the Department of Meteorology, Malaysia and high coefficient of determination with R2 value of 0.99 (RMSE value = 4.7%) and 0.90 (RMSE value = 0.7k) were found for both temperature and humidity respectively.

1. Introduction

Solar irradiance is the power measured on earth radiate by the sun in form of electromagnetic radiation. It is the primary source of energy for earth and it is responsible for the suitable terrestrial condition for all life as well as meteorological phenomena. Radiative transfer model and atmospheric model are the essential tools used for the prediction of solar irradiance. Accuracy of radiative transfer model depends on the quality of atmospheric model used [1]. Static atmospheric models are used in radiative transfer model as the reference and source of input parameter in the process of calculating the attenuation of the solar irradiance. Calculation of such irradiance need masses of atmospheric

· To whom any correspondence should be addressed parameters and comprehensively, these atmospheric parameters are provided by the static atmospheric model.

The intensities of solar irradiance are reduced when propagating through the atmosphere. The radiation was absorb and scattered by the atmospheric constituent. The magnitude of the atmospheric effect was based on the atmospheric characteristic and path length of the propagation[1]. The characteristic of the atmosphere is categorized based on latitude and geometrical characteristic[2]. The atmospheric characteristic in Malaysia is similar with other countries that lies on the equatorial where the humidity is relatively higher compared with other latitude. Geometrically, higher concentration of water vapor in the lower atmosphere was recorded in Malaysia compared to other places with the same latitude and that leads to the main aim of this study which is to develop a local atmospheric model that is important to differentiate the atmospheric characteristic of Malaysia and to produce a better accuracy when come to the implementation of atmospheric correction.

2. Data

Ten years of Atmospheric Infrared Sounder (AIRS) data (consists of temperature profile, geopotential height profile, water mixing ratio profile and the humidity profile) of Peninsular Malaysia (N7°0' E99°45' – N1°15' E104°25') was acquired from Goddard Earth Sciences Data and Information Services Center (GES DISC).

The Atmospheric Infrared Sounder (AIRS) is a high spectral resolution infrared sounder attach on Aqua satellite belong to National Aeronautics and Space Administration (NASA). It measured global atmospheric aerosol, surface emissivity, temperature, ozone, trace gas, and vertical profile of water vapour and temperature in step of 50-100 hPa. The instrument with 2378 channels measured infrared radiance from 3.74 micrometer to 15.4 micrometer[3]. The data used was recorded with ascending node at 1.30pm ±15min in every 2~3 days for equatorial region. The AIRS is an important instrument for the climate study and will significantly improve the weather prediction in future [4].

3. Methodology

3.1. Geopotential and Geometric Height calculation

AIRS data were given in the function of pressure where the pressure was converted into height using suitable algorithm. Geopotential height is defined as "the height of a given point in the atmosphere in unit proportional to the potential energy of unit mass at this height relative to the sea level" by the European centre for Medium-Range Weather Forecasts (ECMWF). The geopotential height were calculated based on pressure, air density, acceleration due to gravity at mean sea level and height of mean sea level. Equation (1) is the general equation used to compute the geopotential height (h) with g_o is the gravity acceleration at mean sea level, p is the pressure and rho is the air density at the point of measurement.

$$h = \frac{p}{rho \times g_o} \tag{1}$$

The geopotential heights are converted into geometric heights (z) by using equation (2) with r_e is the radius of the earth.

$$Z = \frac{hr_e}{gr_e - h} \tag{2}$$

3.2. Cumulative Vertical Water Column

Vertical water column (*vwc*) was derives from the profile of H_2O mixing ratio, temperature, geometric height and pressure using equation (3) with *wmr* is the water mixing ratio and ϱ is the air density.

$$vwc_h = \int_h^{h_o} (wmr_h \times \rho_h \times 10^{-4}) \tag{3}$$

The air density in the function of height (ρ_h) was calculated using ideal gas law in equation (4) with p_h and t_h is the pressure and temperature respectively in the function of height and r_d is gas constant (287.058 J kg^{-1} K^{-1}).

$$\rho_h = P_h (R_d T_h)^{-1} \tag{4}$$

3.3. Compilation of the atmospheric model

This study provides an average atmospheric model for Peninsular Malaysia. The mean values for every pressure level of each atmospheric profile were used as the standard value in the atmospheric model. The model was compiled in the step of 50 to 100hpa.

4. Result and Assessment

4.1. Temporal Variation Analysis

Temporal variation analysis was done on relative humidity, water mixing ratio and temperature profile to detect the variation of the data with time. Gradient of each profile were extracted from linear equation generated by the linear regression. The gradients are translated into percentage to indicate the magnitude of changes value in each profile for the past ten years. Changes of each profile are shown in table 1 where these changes were record in the scale of ten years.

Table 1. Time variation of atmospheric profile in the past ten years.

Pressure (hpa)	Temperature (%)	Humidity (%)	Mixing Ratio (%)
1000	0.028	-0.057	0.175
925	0.019	0.064	0.123
850	0.018	0.176	-0.145
700	0.018	0.137	-0.027
600	0.001	0.268	0.224
500	-0.020	0.226	0.429
400	-0.033	0.250	0.261
300	-0.027	0.071	-0.215
250	-0.022	-0.273	-0.375
200	0.001	-0.158	-0.011
150	-0.009	-0.219	0.000
100	-0.039	0.170	0.000

Maximum changes was detected on the water mixing ratio with an average increment of 0.003% annually while the minimum change is detected on the temperature with 0.002% (0.6ºC) increment in decade. The result shows the profile included in the analysis had a negligible time variation (less than

0.003% anually). This concludes that there is no variation of time and there is no necessary to include time parameter in the atmospheric model.

4.2. Assessment

The result for static atmospheric model is given in Table 2. The profiles in the atmospheric model include geometric height, geopotential height, pressure, water column, relative humidity, and temperature.

The results of the atmospheric model were assessed based on the measured meteorological data (temperature and humidity) provided by the Department of Meteorology, Malaysia. Result between the atmospheric model and measured data shows high coefficient of determination with R^2 value of 0.997 (RMSE value = 4.7%) and 0.907 (RMSE value = 0.7k) for temperature and humidity respectively.

Table 2. Local static atmospheric model for Peninsular Malaysia.

Pressure (hpa)	*h* (m)	*gph (m)*	H2o mixing ratio (g/kg)	Water column (cm)	*rh* (%)	*t* *(k)*
1000	74.5	74.5	15.766	4.051	76.67	303.813
925	772.4	772.3	13.248	2.938	78.99	299.123
850	1514.9	1514.5	8.415	2.117	62.51	293.998
700	3175.2	3173.6	5.516	1.046	52.55	284.456
600	4451.9	4448.8	4.146	0.559	41.47	276.963
500	5915.9	1910.4	2.259	0.232	45.87	268.282
400	7638.4	7329.2	0.844	0.070	40.71	256.676
300	9740.4	9725.5	0.233	0.012	37.23	241.655
250	11005.3	10986.2	0.080	0.004	36.72	230.876
200	12456.3	12451.6	0.024	0.001	39.79	218.266
150	14271.9	14239.9	0.005	0.001	50.40	206.369
100	16635.9	16592.4	0.002	0.000	27.17	190.898

The atmospheric model was applied on SMARTS2 radiative transfer model for predicting the solar irradiance. The total solar irradiance was assessed with the ground measured data by AERONET. Since July 2012, solar flux data were recorded by the Aerosol Robotic Network (AERONET) in Peninsular Malaysia. The AERONET station is located at Universiti Sains Malaysia, Penang, Malaysia (latitude: 5.35838 N and Longitude: 100.30231 E, Elevation: 51.0 Meter). The data recorded have an average of 30% solar irradiance under cloud free condition. Under a cloud covered condition, the intensity recorded by the pyranometer is having a huge variation due to the uncertainties of the cloud cover whereas for the cloudless condition, the intensity is stable with minimum variation since there is not much effect from the clouds (please refer to figure 1 with the peak solar flux were at 912wm^{-2} at zenith angle of 30°). Statistic analysis was done using equation (5) for the identification of central flux where $\mathbf{L_i}$ is the lower limit of the modal class, $\mathbf{f_i}$ is the absolute frequency of the modal class, $\mathbf{f_{i-1}}$ is the absolute frequency immediately below the modal class, $\mathbf{f_{i+1}}$ is the absolute frequency immediately after the modal class and $\mathbf{a_i}$ is the width of the class containing the modal class.

$$M_0 = L_i + \frac{f_i - f_{i-1}}{(f_i - f_{i+1}) + (f_i - f_{i-1})} . a_i \qquad (5)$$

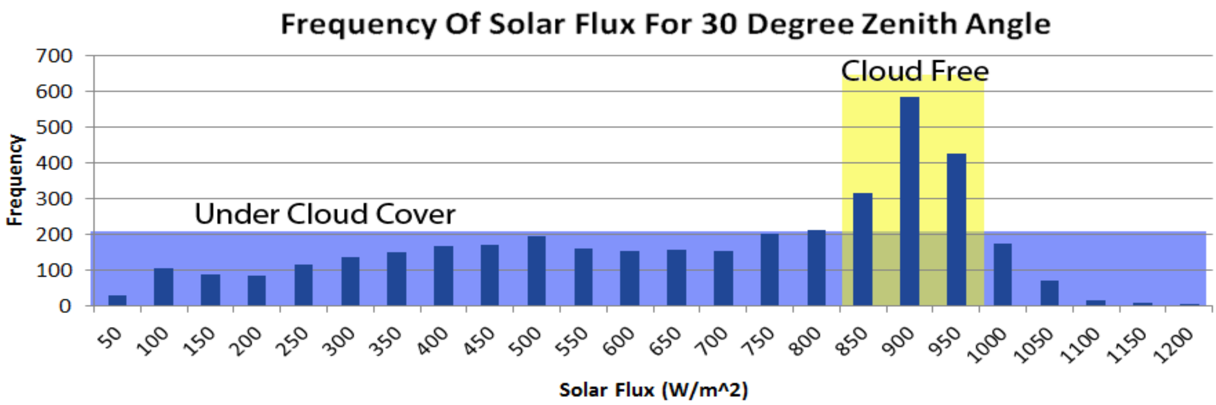

Figure 1. Frequency of solar irradiance at 30° zenith angle.

Since the radiative transfer model was designed to predict solar irradiance under cloudless condition, irradiance data that had been identified as under cloud cover effect will not be considered. Central solar flux for every 15 ° zenith angle (from 0 ° to 60°) for each month was tested with the predicted solar irradiance for the assessment of model.

The measured and calculated central solar fluxes are shown in table 3 and 4 respectively. RMSE are calculated based on the two set of data and is shown in table 5 with average value and RMSE for each zenith angle.

Table 3. Measured central solar flux

Pressure (hpa)	60°	45°	30°	15°	0°
August	406.81	624.02	840.69	951.13	N/a
September	384.87	666.47	878.20	979.36	975
October	455.21	680.55	903.89	977.50	N/a
November	453.62	686.16	917.24	N/a	N/a
December	462.08	671.42	880.43	N/a	N/a

Table 4. Calculated central solar flux

Pressure (hpa)	60°	45°	30°	15°	0°
August	431.93	670.50	858.37	977.71	1018.58
September	438.27	680.34	870.97	992.06	1033.53
October	468.11	726.66	930.26	1059.60	1103.89
November	453.39	703.81	901.01	1026.28	1069.18
December	458.00	710.97	910.17	1036.72	1080.05

Table 5. The average and RMSE for calculated central solar flux.

	60°	45°	30°	15°	0°
Average	449.94	698.456	894.156	1018.474	1061.046
RMSE	0.060	0.051	0.024	0.050	0.055

5. Conclusion

The atmospheric model developed was assessed based on the measured meteorological data provided by the Department of Meteorology, Malaysia. The model is then applied on SMARTS2 radiative transfer model [5][6]for the calculation of solar irradiance on different zenith angle. The results were then assessed with solar flux data from AERONET.

Both the assessment for the atmospheric model and solar irradiance show a high coefficient of determination with the R^2 value of 0.95 and 0.97 respectively. The analysis on atmospheric data recorded by AIRS shows an average of 0.003% changes detected annually of 0.03% for a decade. It is wise to assume that there is no time variation for the AIRS data based on the result; hence time parameter is not necessary to be include in the atmospheric model. The assessment of the atmospheric model shows a very high coefficient of determination on the measured data with RMSE of 4.7% and 0.7k for humidity and temperature respectively. The application of atmospheric model in SMARTS2 radiative transfer model shows a very reliable solar irradiance data where the calculated irradiance was assess with AERONET data with average RMSE value of 0.5 Wm^{-2} for each zenith angle.

Acknowledgments

A heartfelt appreciation is given by authors to Universiti Teknologi Malaysia and the Ministry of Higher Education (MOHE), Malaysia for funding part of this study under the research scheme “Fundamental Research Grant Scheme (FRGS)” with the VOT number 4F091.

References

[1] Muhammad Iqbal. 1983 A*n Introduction to Solar Radiation*

[2] Fredurick k L and Edward j. T 2007 *The atmosphere (tenth edition).*

[3] Wu Xuebao, Li Jun, Zhang Wenjian and Wang Fang 2005 *Advance in Atmpspheric Sciences.* **22, 5** 647–654

[4] Goldberg M D., Y Qu, L M McMillin, W Wolf, L Zhou and M Divakarla

[5] Gueymard C A 2001 Solar Energy. **71** 325-346.

[6] Gueymard C A 2004 Solar Energy. **76** 423-453.

[7] Annette Hammer, Detley Heinemann, CarstenHoyer, Rolf Kuhlemann, Elke Lorenz, Richard Muller and Hans George Beyer 2003 *Remote Sensing for Environment* **86** 423-432

[8] Bo Leckner 1977 *Solar Energy*. **20** 143-150.

[9] Brine D T and M Iqbal 1983 *Solar energy* **30** 447–453

[10] Justus C G and Johnson D L 1999 *the NASA/MSFC Global Referrence Atmospheric Model, Nasa/TM-1999-209630.*

[11] Justus C G and Leslie F W 2008 *the NASA/MSFC Earth Global Referrence Atmospheric Model-2007 Version, Nasa/TM-2008-215581*

[12] Aronova E S, Grilikhes V A, Shvarts M Z and Timoshina N H 2008 *Photovoltaic Specialists Conference.*

[13] Gregg W W and Carder K L 1990 *Journal of Limnology and Oceanography* **35,8** 1657-1675

[14] Koshelhov Y P 1983 *Adv. Space Re.* **3** 3-16

[15] Koshelhov Y P 1987 *Adv. Space Re.* **7** 83-96

[16] Minzner R A 1976 *Reviews of geophysics* **15,3** 375-384