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

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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...
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 absorbed 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.

\[
h = \frac{p}{\rho \times g_o}
\]  

(1)

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

\[
z = \frac{h r_g}{g r_e^2 - h}
\]  

(2)
3.2. Cumulative Vertical Water Column

Vertical water column (vwc) was derived from the profile of H₂O mixing ratio, temperature, geometric height and pressure using equation (3) with \(wmr\) is the water mixing ratio and \(\rho\) is the air density.

\[
v_{\text{vwc}} = \int_{h_1}^{h_2} (wmr_h \times \rho_h \times 10^{-4}) dh
\]  

(3)

The air density in the function of height \((\rho_h)\) 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\(^{-1}\)).

\[
\rho_h = \frac{p_h}{R_d T_h}
\]  

(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.

| 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% annually). 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.

| 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 $L_i$ is the lower limit of the modal class, $f_i$ is the absolute frequency of the modal class, $f_{i+1}$ is the absolute frequency immediately below the modal class, $f_{i+1}$ is the absolute frequency immediately after the modal class and $a_i$ is the width of the class containing the modal class.

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

(5)
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.

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