Evaluation of Aerosol Optical Depth on Harvesting of Solar Radiation

WIRAT AI HIM¹, M.A. ALGHOUL², SYAMSYIR AKMAL SENAWI², K. SOPIAN², M.Y. SULAIMAN², M.YAHYA², B. ALI², SOHIF MAT² AND A. ZAHARIM²

¹Department of Physics, Faculty of Science and Technology, Sultan Idris University of Education, 35900 UPSI Tanjung Malim, Perak, MALAYSIA.
Tel: +6054506144 Fax:+6054583616, Email: wirataihim@fst.upsi.edu.my

²Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, MALAYSIA.
Tel:+60389214600 Fax:+60389214593, Email: dr.alghoul@gmail.com

Abstract:-Evaluation of the effect of two important aspects in Aerosol Optical Depth (AOD) on direct radiation normal to the beam at the earth surface, direct, diffuse and global radiation incident upon a horizontal surface have been carried out. Bird model was used as a methodology to evaluate the effect of AOD in the context of radiation that falls on the earth surface. The first analysis is the relation between the values of AOD and the output from the Bird Model with in differences of AOD input values. Second analysis is the relation between the output from Bird Model and time when the value of AOD for short wavelength was fixing and long wavelength was manipulate. The first relation was interpreted in the graph of output for the four types of radiation versus the input value of AOD. Times that chose for the analysis of this graph were in the morning at 8 am, noon at 1 pm and afternoon at 7 pm. The Plot shows that the direct radiation normal to the beam at the earth surface, direct and global radiation incident upon a horizontal surface were inversely proportional to AOD for the times chosen respectively. While for the diffuse radiation was directly proportional to AOD for the times chosen respectively.

Key-Word:-Aerosol Optical Depth, Bird model, solar radiation, wavelength

1. INTRODUCTION
The atmosphere is composed of molecules of gas and small solid and liquid particles suspended in the air, called aerosols. Some aerosols enter the atmosphere as particles from volcanoes, sea spray, dust, smoke, wind erosion of surface soil, and air pollution from human activities such as burning fossil fuels and biomass (e.g., wood, dung, dried leaves), plowing, and digging [1]. Aerosols are tiny particles in the 0.001 to 100 µm range suspended in the atmosphere and can be solids such as smoke and dust or liquids such as haze droplets. Either naturally occurring or produced by human activities, aerosols have an impact on respiratory health and global climate and weather [2]. Remote-sensing scientists often talk about aerosols in terms of their optical depth, which indicates how much of the incoming sunlight aerosols prevent from reaching the Earth’s surface [3]. Aerosols are one of the greatest sources of uncertainty in climate modeling. Aerosols vary in time in space and can lead to variations in cloud microphysics, which could
Determining optical properties such as aerosol optical thickness is crucial to estimate the direct influence on radiative forcing. Aerosol optical depth (AOD) is a quantitative measure of the extinction of solar radiation by aerosol scattering and absorption between the point of observation and the top of the atmosphere. It is a measure of the integrated columnar aerosol load and the single most important parameter for evaluating direct radiative forcing. AOD can be determined from the ground through measurements of the spectral transmission of solar radiation through the atmosphere using rather simple and relatively inexpensive instruments pointed directly at the sun called sun photometers or filter radiometers [5]. The larger the optical thickness at a particular wavelength, the less light of that wavelength reaches Earth’s surface. Measurement of aerosol optical thickness can provide important information about the concentration, size distribution, and variability of aerosols in the atmosphere. This information is needed for climate studies, for comparison with satellite data and to understand the overall effects of aerosols.

Optical thickness is a measure of the amount of direct sunlight reaching a detector that responds (theoretically) to a single wavelength of light. (In practice, all detectors respond to a range of wavelengths.) Optical depth is another commonly used name for the same measure these two terms is interchangeable. Optical thickness (or optical depth) is affected by molecular (Rayleigh) scattering, gaseous absorption, and absorption or (mostly) scattering by aerosols. The portion of optical thickness due to aerosols is called aerosol optical thickness or aerosol optical depth, $\tau$.

2. MATHEMATICAL ANALYSIS
A typical aerosol optical thickness value for visible light in clear air is roughly 0.1. A very clear sky may have an AOD of 0.05 or less. Very hazy skies can have AOD of 0.5 or greater. It may be easier to understand the concept of optical thickness when it is expressed in terms of the percentage of light that is transmitted through the atmosphere, according to this formula:

$$\text{Percent of transmission} = 100 \times e^{-\tau} \quad (1)$$

where $\tau$ is optical thickness at a particular wavelength. This calculation gives the percentage of light at a particular wavelength that would be transmitted through the atmosphere if the sun were directly overhead. For an optical thickness of 0.1, the percent transmission is about 90.5%. Wavelength, optical thickness, and atmospheric turbidity (haziness) are related through Angstrom’s turbidity formula:

$$\tau = \beta \cdot \lambda^{-\alpha} \quad (2)$$

where $\beta$ is Angstrom’s turbidity coefficient, $\lambda$ is wavelength in microns, and $\alpha$ is the Ångstrom exponent. $\alpha$ and $\beta$ are independent of wavelength, and can be used to describe the size distribution of aerosol particles and the general haziness of the atmosphere. For two different wavelengths,

$$\tau_1 = \beta \cdot \lambda_1^{-\alpha} \quad (3)$$
$$\tau_2 = \beta \cdot \lambda_2^{-\alpha} \quad (4)$$

From which

$$\tau_1/\lambda_1^{-\alpha} = \tau_2/\lambda_2^{-\alpha} \quad (5)$$

Solving for $\alpha$:

$$\alpha = \ln(\tau_1/\tau_2)/\ln(\lambda_2/\lambda_1) \quad (6)$$

A typical range for $\alpha$ is 0.5-2.5, with an average for natural atmospheres of around 1.3±0.5. Larger values of $\alpha$, when the $\tau_2$ value for the larger wavelength ($\lambda_2$) is much smaller than the $\tau_1$ value for the smaller wavelength ($\lambda_1$), imply a relatively high ratio of small particles to large ($r>0.5 \mu m$) particles. As $\tau$ for the larger wavelength approaches the $\tau$ for the smaller wavelength, larger particles dominate.
the distribution and $\alpha$ gets smaller. It is not physically reasonable for the $\tau$ value of the larger wavelength to equal or exceed the $\tau$ value of the smaller wavelength.

Now calculate $\beta$ from either wavelength:

$$\beta = \tau_1 \lambda_1^\alpha = \tau_2 \lambda_2^\alpha \quad (7)$$

where $\lambda$ must be expressed in microns (500 nm = 0.500 $\mu$). $\beta$ values of less than 0.1 are associated with a relatively clear atmosphere, and values greater than 0.2 are associated with a relatively hazy atmosphere. Given $\tau$ at two different wavelengths, the $\tau$ at a third wavelength can be inferred for the same atmospheric conditions. Rewrite (7) and solve for $\tau_3$ using either the first or second wavelength:

$$\ln\left(\frac{\lambda_3}{\lambda_1}\right)\alpha = \ln\left(\frac{\tau_1}{\tau_3}\right) = \ln(\tau_1) - \ln(\tau_3) \quad (8)$$

$$\ln(\tau_3) = \ln(\tau_1) - \ln\left(\frac{\lambda_3}{\lambda_1}\right)\alpha$$

$$\tau_3 = \exp\left[\ln(\tau_1) - \ln\left(\frac{\lambda_3}{\lambda_1}\right)\alpha\right] \quad (9)$$

This calculation is useful when $\tau$ values determined with one instrument must be compared to values from another instrument that uses different wavelengths. The ratio of optical depth at two different wavelengths is related to slope of the aerosol size distribution. Higher ratio values indicate areas of steeper size usually due to pollution or biomass burning, and lower values indicate marine and dust aerosols [6].

Sunlight reaching the Earth's surface unmodified by any of the atmospheric processes is termed direct solar radiation. Solar radiation that reaches the Earth's surface after it was altered by the process of scattering is called diffused solar radiation. Not all of the direct and diffused radiation is available at the Earth's surface. Some of the radiation received at the Earth's surface is redirected back to space by reflection. Of all the sunlight that passes through the atmosphere annually, only 51 % is available at the Earth's surface; to heat the Earth's surface and lower atmosphere, evaporate water, and run photosynthesis in plants. Of the other 49 %, 4 % is reflected back to space by the Earth's surface, 26 % is scattered or reflected to space by clouds and atmospheric particles, and 19 % is absorbed by atmospheric gases, particles, and clouds [7].

Therefore about 1000 W/m$^2$ of the incident solar radiation reaches the earth's surface without being significantly scattered. This radiation, coming from the direction of the sun, is called direct normal irradiance (or beam irradiance). Some of the scattered sunlight is scattered back into space and some of it also reaches the surface of the earth. The scattered radiation reaching the earth's surface is called diffuse radiation. Some radiation is also scattered off the earth's surface and then re-scattered by the atmosphere to the observer. This is also part of the diffuse radiation the observer sees. This amount can be significant in areas in which the ground is covered with snow. The total solar radiation on a horizontal surface is called global irradiance and is the sum of diffuse radiation incident upon a horizontal surface plus the direct radiation incident upon a horizontal surface [8].

3. METHODOLOGY

Bird Model software [9] is used to evaluate the effect of AOD on solar radiation potential. Bird model output are four types of radiation that falls on the earth such as direct radiation normal to the beam at the earth surface, direct, diffuse and global radiation incident upon a horizontal surface. Two conditions of AOD at different wavelength were analyzed simultaneously. The first condition is the aerosol optical depth at 500 nm wavelength which is identified as long wavelength with typical optical thickness ranged from 0.02 to 0.50. The second condition was analyzed for the aerosol optical depth at short wavelength 380 nm ranged from 0.1 to 0.5. The analysis was carried out at 8 am, 1 pm and 7 pm. Input data Sheet of Bird model is shown in table 1.
Table 1: Input data sheet of Bird model for solar radiation calculation.

<table>
<thead>
<tr>
<th>Calculation of solar position based on NOAA's functions and solar radiation data on Bird and Holstein's model.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong></td>
</tr>
<tr>
<td>Latitude in decimal degrees (positive in northern hemisphere)</td>
</tr>
<tr>
<td>Longitude in decimal degrees (negative for western hemisphere)</td>
</tr>
<tr>
<td>Time zone in hours relative to GMT (GMT= 0, MST= -7, MST= -6, EDT= -5)</td>
</tr>
<tr>
<td>Daylight savings time (yes / no / 1)</td>
</tr>
<tr>
<td>Start date to calculate solar position and radiation</td>
</tr>
<tr>
<td>Start time</td>
</tr>
<tr>
<td>Time step (hours)</td>
</tr>
<tr>
<td>Horizontal distance to calculate solar position and radiation</td>
</tr>
<tr>
<td>Atmospheric pressure (mb, sea level = 1013)</td>
</tr>
<tr>
<td>Water vapor thickness of atmosphere (cm):  typical 0.0 to 0.4 cm</td>
</tr>
<tr>
<td>Water vapor thickness of atmosphere (cm): typical 3.3 to 5.5 cm</td>
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<tr>
<td>Excess solar optical depth at 500 nm (typical 0.02 to 0.5)</td>
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<tr>
<td>Aerosol optical depth at 380 nm (typical 0.1 to 0.5)</td>
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<tr>
<td>Forward scattering of incoming radiation (typical 0.5)</td>
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<tr>
<td>Surface albedo (typical 0.2 for land, 0.3 for vegetation, 0.9 for snow)</td>
</tr>
</tbody>
</table>


4. DISCUSSION AND RESULTS

Figures 1 and 2 show that there is very conspicuously exponential reduction for the direct radiation normal to the beam at the earth surface when the value of AOD increased. Global radiation incident upon a horizontal surface is almost constant when AOD increased. Direct and diffuse radiation incident upon a horizontal surface decrease and increase respectively slightly when AOD increase.

Diffuse radiation incident upon a horizontal surface increase by the increment of AOD is shown in Fig. 3. This increment is very clear at 1 pm compare to Fig 1 (8am) and Fig 2 (7pm) resulted from the foaming of particles at thick level in atmosphere. The thickness of the particles from the hazes and air pollution will reduce the amount of solar radiation that falls on earth surface. At the same time this condition will created the green house effect phenomena. As a result, this green house effect will affect the diffuse radiation to increase greatly and this will make the temperature raised and earth surface to be hotter. The raising of the earth temperature is known as global warming resulted from the foaming of thick layer which can be solids such as smoke and dust or liquids such as haze droplets. As a result, the increment of AOD will increase the thickness of the haze droplets contain in the atmosphere and resulting from that, the direct radiation from sun penetrated the atmosphere will reduce.
Fig. 3: Radiations types versus aerosol optical depth (AOD) at 500nm (typical 0.02-0.50) and 380nm (typical 0.1) 1 January 2005 at 1 p.m.

Fig. 4 shows that diffuse radiation incident upon a horizontal surface increase as AOD increase. During 24 hours, the highest increment of diffuse radiation due to the effect of AOD increment is recorded at 1 p.m. The increment of diffuse radiation is very affected due to the six sets of AOD increment and the it are very obvious compared to the others radiation such as direct radiation normal to the beam, direct radiation incident upon a horizontal surface and global radiation incident upon a horizontal surface. From the graph also, it shown that the available of solar radiation is from 8 a.m. to 7 p.m.

Fig. 5: Direct radiation normal to the beam at the earth surface versus time for AOD at 500nm (typical 0.02-0.50) and 380nm (typical 0.5).

The most similar conditions for the reduction of direct radiation and global radiation due to the increment of AOD are shown in Fig. 5, Fig. 6 and Fig. 7. From the graphs, the gap of the radiations reduction for the six sets of AOD increment is not very large. It shows that the reduction of direct radiation normal to the beam, direct radiation incident upon a horizontal surface and global radiation incident upon a horizontal surface are not very affected by the increment of AOD compared to diffuse radiation. The area under the curve in Fig. 5 is larger than the Fig. 6 and Fig. 7. It shown that the amount of the direct radiation normal to the beam that falls on the earth surface is higher than the others types of radiations discussed in this study.

Fig. 8 shows the four types of radiations at the highest AOD. It shown that the global radiation which is the summation of direct radiation incident upon a horizontal surface and diffuse radiation incident upon a horizontal surface is larger than direct radiation normal to the beam at the earth surface. This conditions is caused the increment of earth temperature which known as global warming due to the increment of AOD.
5. CONCLUSION

The results on the value of AOD for the long wavelength at 500 nm (typical 0.02 to 0.5) and short wavelength at 380 nm (typical 0.1 to 0.5) from the Bird model show that the direct radiation normal to the beam at the earth surface is very affected with increment of AOD. Direct radiation normal to the beam reduced when AOD increased. This is because most of the incoming radiation from the sun into earth surface were scattered and absorbed by the formation of the thick AOD. Only a few amount of direct radiation can pass through the atmosphere as AOD increase. Resulted from the increment of AOD also affected the increment for the diffuse radiation which caused the phenomena of earth temperature raising which known as global warming. The increment of AOD thickness resulted from the foaming of thick layer in the atmosphere which can be solids such as smoke and dust or liquids such as haze droplets.

References:


