Moderate Imaging Resolution Spectroradiometer (MODIS) Aerosol Optical Depth Retrieval for Aerosol Radiative Forcing

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Abstract. The present study uses the Aerosol Optical Depth (AOD) retrieved from Moderate Imaging Resolution Spectroradiometer (MODIS) data for the period from January 2011 until December 2015 over an urban area in Kuching, Sarawak. The results show the minimum AOD value retrieved from MODIS is -0.06 and the maximum value is 6.0. High aerosol loading with high AOD value observed during dry seasons and low AOD monitored during wet seasons. Multi plane regression technique used to retrieve AOD from MODIS (AOD_{MODIS}) and different statistics parameter is proposed by using relative absolute error for accuracy assessment in spatial and temporal averaging approach. The AOD_{MODIS} then compared with AOD derived from Aerosol Robotic Network (AERONET) Sunphotometer (AOD_{AERONET}) and the results shows high correlation coefficient (R²) for AOD_{MODIS} and AOD_{AERONET} with 0.93. AOD_{MODIS} used as an input parameters into Santa Barbara Discrete Ordinate Radiative Transfer (SBDART) model to estimate urban radiative forcing at Kuching. The observed hourly averaged for urban radiative forcing is -0.12 Wm⁻² for top of atmosphere (TOA), -2.13 Wm⁻² at the surface and 2.00 Wm⁻² in the atmosphere. There is a moderate relationship observed between urban radiative forcing calculated using SBDART and AERONET which are 0.75 at the surface, 0.65 at TOA and 0.56 in atmosphere. Overall, variation in AOD tends to cause large bias in the estimated urban radiative forcing.

1. Introduction

The urban pollution sources are quite variable in space and time. The impacts of urban aerosol towards environment and the regional and global air quality. Atmospheric aerosols play an important role in the global energy balance by scattering and absorbing the solar and terrestrial radiation (direct effect), as well as by acting as cloud condensation (indirect effect) [1]. It can be derived from natural as well as anthropogenic sources especially the urban pollution which is quite variable in space and time. These aerosols are known to affect the air quality, human health and Earth radiation budget [2]. The direct effect due to aerosols as effect of both natural and anthropogenic on the radiation budget primarily due to scattering and absorption of radiation by aerosols and is measured in terms of watts per square meter (Wm⁻²) or also known as aerosol radiative forcing (ARF) [3]. The values of ARF at top of atmosphere (TOA) and surface are important parameter in the quantification of the impact of aerosols towards climate change. The largest uncertainties in estimating the changes in radiation budget due to high spatial variability of aerosols and lack of an adequate information regarding aerosol
radiative properties [1]. Therefore, an understanding of the changes urban aerosols over time are very important to predict the effect of warming and cooling towards the regional area.

Different ground and satellite based remote sensing techniques helps to provide a systematic retrieval of aerosol optical properties on the global and regional scale [2]. Satellite remote sensing is the only technology help to observe the spatial and temporal variations of aerosol properties and have been used broadly in estimating aerosol ARF. Based on the remote sensing observations, Moderate Resolution Imaging Spectroradiometer (MODIS) data significantly can be used to estimate ARF value under clear sky conditions [4]. While ground based remote sensing such as Aerosol Robotic Network (AERONET) is useful in estimating continuous optical properties for aerosol in real time monitoring and also can be used for validation [5]. One of the important parameter in assessing the ARF value is Aerosol Optical Depth (AOD). It defined as extinction coefficient of aerosol loading measured in vertical column of the atmosphere [6]. As stated by [7], the changes in surface ARF value can primarily governed by the magnitude of AOD values which consistent with the aerosol loading.

The objective of this study is to investigate the influence of urban aerosols on the estimation of ARF by using AOD retrieved from MODIS (AOD\textsubscript{MODIS}) over Kuching area. In this study, AOD\textsubscript{MODIS} are retrieved by multi plane regression technique. The combination technique with minimum distance technique and the usage of relative absolute error are introduced for accuracy assessment in spatial and temporal averaging approach and compared with AOD derived from AERONET (AOD\textsubscript{AERONET}). Next, the AOD\textsubscript{MODIS} used as an input parameter into radiative transfer model which is Santa Barbara Discrete Ordinate Radiative Transfer (SBDART) for conducting quantitative estimation of urban radiative forcing.

2. Data measurement and study site

Terra MODIS data Level 2 (Collection 5) provides data used to study aerosol climatology and highly suitable for characterization of aerosol properties spatial resolution of 10km x 10km and can be downloaded at http://ladsweb.nascom.nasa.gov/data/search.html. AERONET is a ground based monitoring aerosol that assess aerosol optical properties and to validate satellite retrievals of aerosol optical properties. The Level 2 AOD at 500nm was used for the analysis and can be downloaded at http://aeronet.gsfc.nasa.gov. The uncertainty in retrieval of AOD under cloud free conditions is <±0.01 for λ>440nm and <±0.02 for shorter wavelengths [5]. The data used for this study is from 2011 until 2015 both for MODIS and AERONET, respectively.

The experimental site for this study is at Kuching with tropical rainforest climate which moderately hot and humid. The wettest seasons are during the North-East Monsoon months (November to March) and dry seasons from June until September every year. Figure 1 shows the location of the study site and location of AERONET Sunphotometer.

![Figure 1. Study site of Kuching, Sarawak and location of AERONET Sunphotometer](image-url)
3. Methodology

3.1. Spatial and temporal averaging approach
Firstly, a time window of ±20 min was chosen with respect to MODIS overpass and a temporal average was compared with the time availability of AERONET. Since air masses are constantly in motion, an air mass captured by MODIS across a certain horizontal span over AERONET station will be sampled by the during a certain time period [8]. Minimum distance technique was performed for MODIS data to calculate the closest pixel of latitude and longitude to the AERONET site and the output were given in column and row pixel. The equation for minimum distance technique in the following way:

\[ R, C = \left( \min \left( (x - x1)^2 + (y - y1)^2 \right) \right) \]  

(1)

Based on Equation 1, x is a longitude for MODIS and AERONET and y is the latitude for MODIS and AERONET. Smaller window sizes (11 x 11 pixels) are used to reduce undesirable errors due to topographic or aerosol types heterogeneity. The spatial average of AOD\text{MODIS} over the AERONET were collocated from pixels lying in ±(1/4º) of latitude (1.491°) and longitude (110.349°) of AERONET station in Kuching, Sarawak.

A table of AOD along with the corresponding latitude and longitude that fall into these pixels was prepared for each of the MODIS data. Based on the MODIS algorithm for the retrieval of AOD, the valid range allowed for AOD was between -0.05 to 5.0. These values are indicative of very clean conditions and allowed in order to avoid an artificial bias in statistics [9]. Based on the tabulated table, the five nearest values lying within the lowest relative absolute error were chosen to compare which produced less error values.

3.2. Multiple Regression Plane Technique
Next, the selected five points values for each of MODIS data available was plotted by using scatter plot with independent variables, latitude and longitude, on the X and Y axes and dependent variable, AOD, on the Z axis in order to perform multiple regression plane technique. These points have been fitted in the form of Equation 2.

\[ Z = aX + bY + c \]  

(2)

By using Equation 2, the predicted AOD\text{MODIS} data for each of the Julian Days can be calculated. The AOD\text{MODIS} data was at the wavelength range 550nm while AOD\text{AERONET} was at 500nm. For easy comparison with AOD\text{MODIS}, AOD\text{AERONET} were interpolated by using Equation 3.

\[ \text{AOD}_{550\text{nm}} = \text{AOD}_{500\text{nm}} \left( \frac{550}{500} \right)^{-\alpha} \]  

(3)

Where \(\alpha\) is the angstrom exponent at wavelength 440/870nm obtained from AERONET data [10]. After that, the relationship between AOD\text{MODIS} is established with AOD\text{AERONET} based on least square regression and it output presented in correlation coefficient (R²).

3.3. Estimation of aerosol radiative forcing
Finally, AOD\text{MODIS} used as an input parameter into SBDART for urban radiative forcing estimation [11]. The net flux at the TOA and surface were computed separately, within the wavelength range from 0.2 to 4.0 μm over 24 h with 1h time intervals. The outcome from SBDART model is the value of instantaneous irradiance which is downwards and upward solar fluxes. Calculation of ARF can be estimated by using Equation 4 with negative values of ARF corresponds to cooling effect while positive values of ARF corresponds to warming effect either at the surface or at TOA [6].
\[ \Delta F = (F_a \downarrow - F_a \uparrow) - (F_n \downarrow - F_n \uparrow) \] (4)

Where \( F_a \downarrow \) and \( F_a \uparrow \) are downward and upward solar fluxes at the surface in the presence of aerosols and \( F_n \downarrow \) and \( F_n \uparrow \) are the same quantity but without aerosols and \( \Delta F \) is the ARF value. The difference between the TOA and surface gives the atmospheric forcing (\( \Delta F_{atm} \)) which represents the energy absorbed in the atmosphere.

4. Results and Discussions

4.1 Variations of Aerosol Optical Depth

The relationship between AOD\textsubscript{MODIS} and AOD\textsubscript{AERONET} can be analyzed for easy comparison because of the same wavelength range at 550nm.

Based on Figure 2, the minimum values for AOD\textsubscript{MODIS} is -0.06 and the maximum value estimated is 6.0 while for AOD\textsubscript{AERONET} the range values were from 0.04 to 2.95. High concentration of aerosol loading presence in Kuching area causes at certain Julian Days were obtained high value for AOD. As resulting by the occurrence of dry season which usually occurs during June until September yearly and also comes from haze episodes and also from urbanization. Study by [12] classified that In Kuching area dominant aerosols occurred in Kuching area urban and continental aerosols. It can be shown that at Julian Day 253 in 2015 there are extremely high value of AOD\textsubscript{MODIS} was retrieved with 6.0 while only 2.9 for AOD\textsubscript{AERONET}. The reason for the overestimation of AOD from MODIS may be due to dry season where the surface is very dry causes higher value for surface reflectance. An error of \( \pm 0.006 \) in measuring the surface reflectance yields an error of \( \pm 0.06 \) in retrieval of AOD [10]. Extremely low AOD value obtained during the wettest seasons from November to March. The inconsistency between aerosol microphysical and optical properties and surface reflectance used in the MODIS are possible reasons for the underestimation of AOD during wet season [13]. The comparison between AOD\textsubscript{MODIS} and AOD\textsubscript{AERONET} can be analyzed by using linear regression technique and shown in Figure 3.
Based on Figure 3, the retrieval algorithm performance can be validated by the statistical parameters of the linear regression which are intercept (A), slope (B) and correlation coefficient ($R^2$). From the result, it shows that the non-zero intercept at $A = -0.1181$ corresponds that the retrieval algorithm is biased at low AOD value due association with a sensor calibration error or an improper assumption on ground surface reflectance and larger errors in surface reflectance lead to larger intercept values [14]. [9] studied on the comparison AOD using MODIS and AERONET where the underestimation of AOD probably due to incorrect characterization of the local aerosols and the predominantly low AOD values being observed. A slope that is different from unity indicates that there are inconsistency between aerosol microphysical and optical properties used in the retrieval algorithm [14] and represents systematic biases in the MODIS retrievals [13]. Slope higher than unity for AOD$_{MODIS}$ at 1.6469 indicates an overestimation of AOD$_{MODIS}$ with respect to AERONET retrieval. There is a strong relationship between AOD$_{MODIS}$ and AOD$_{AERONET}$ with the value for $R^2$ is 0.932 and the mean absolute percentage error (MAPE) was found to be 12% and root mean square error (RMSE) is 0.47.

4.2 Comparison between AOD estimated by SBDART and AERONET

The reliability of the ARF calculated by the AOD$_{MODIS}$ using SBDART can be compared with ARF derived from AERONET and can be shown in Figure 4.
Figure 4 is the hourly averaged ARF from SBDART model and being compared with the ARF derived from AERONET. The $R^2$ value of ARF estimates calculated by SBDART and AERONET are 0.75 at the surface, 0.65 at TOA and 0.56 in atmosphere. The observed hourly averaged for urban radiative forcing is -0.12 Wm$^{-2}$ for top of atmosphere (TOA), -2.13 Wm$^{-2}$ at the surface and 2.00 Wm$^{-2}$ in the atmosphere. In general, the ARF value at TOA and surface are negative, whereas ARF in atmosphere is positive because energy have been absorbed into the aerosol layer [4]. These results show that ARF derived from SBDART by using AOD$_{MODIS}$ is in moderate agreement with that calculated by AERONET. It can be suggested that the AOD$_{MODIS}$ could also be used to estimate ARF using SBDART model with some improvements in obtaining accurate ARF values.

5. Conclusion
The aerosol concentration and urban radiative forcing over a period of five years had been analyzed at urban area of Kuching. The spectral variations of AOD at Kuching are based on the seasonal distinctive features with high AOD observed during dry seasons (June to September) and low concentration of AOD during wet seasons from November to March. The urban radiative forcing within the atmosphere is higher during dry seasons when AOD values also higher indicating higher absorption in the atmosphere. The comparison of the urban radiative forcing estimated from SBDART model with that obtained from AERONET is also an important aspect of the present study. The comparison reveals that urban radiative forcing estimated from SBDART are highly correlated at the surface but moderate relationship obtained for urban radiative forcing at TOA and in the atmosphere. In this comparison not all the ARF value been taken during the observation period. This is because there are only few months of data with the flux by derived by the AERONET and lack of AOD data. Though the results are preliminary and comes from limited observational results, the outcome from the study might significantly influence the urban radiative forcing over Kuching thus contributing the warming and cooling effect at Malaysia area.

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References
[1] Intergovernmental Panel on Climate Change (IPCC) 2007
[2] Kaufman Y J, Tanre D and Boucher O 2002 Nature 419 (6903) 215-223
[3] Srivastava A K, Singh S, Tiwari S and Bisht D S 2012 Environ. Sci. Pollut. Res. 19(4) 1144-1158
[4] Xu H, Guo J, Ceamanos X, Roujean J L, Min M and Carrer D 2016 Atmospheric Environment 141 186-196
[5] Holben B N, Eck T F, Slutsker I, Tanre D, Buis J P, Setzer A, et al 1998 Remote Sensing of Environment 66(1) 1-16
[6] Alam K, Trautmann T, Blaschke T and Majid H 2012 Atmospheric Environment 50 234-245
[7] Dhar P, De B K, Banik T, Gogoi M M, Babu S S and Guha A 2017 Science of the Total Environment 580 499-508
[8] Ichoku C, Chu D A, Mattoo S, Kaufman Y J, Remer L A, Tanre D, Slutsker I and Holben B N 2002 Geophysical Research Letters 29(12) 1-4
[9] Lanzaco B L, Olcese L E, Palancar G G and Toselli B M 2016 Aerosol and Air Quality Research 16 1509-1522
[10] Tripathi S N, Dey S, Chandel A, Srivastava S, Singh R P and Holben B N 2005 Ann. Geophys 23 1093-1101
[11] Ricchiazzi P, Yang S, Gautier C and Sowle D 1998 Bulletin of the American Meteorological
Society 79(10) 2101-2114

[12] Jalal K A, Asmat A and Ahmad N 2012 Advanced Materials Research 518-523 5734-5737

[13] More S, Pradeep Kumar P, Gupta P, Devara P C S and Aher G R 2013 Aerosol and Air Quality Research 13(1) 107-121

[14] Zhao T X P, Stowe L L, Smirnov A, Crosby D, Sapper J and McClain C R 2002 American Meteorological Society 59 294-312