Background Optical Depth Correction over Urban Areas to Improve Land Aerosol Retrieval from Himawari-8

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Abstract. A conventional clear-sky minimum reflectance method, which has been widely used for AOD retrieval from geostationary satellites, usually has less accuracy over urban than other land areas. Urban areas usually have more complex surface properties and various aerosol types from different emission sources. When the surface reflectance is calculated from the clear-sky minimum reflectance, background aerosol optical depth (BOD) is assumed to be closed to zero. This assumption generates larger surface reflectance which leads to underestimation of AOD retrieved. This study proposed a correction for BOD value to be applied for AOD retrieval primary over urban areas where the pollution or natural source aerosol is persistent for long term. The study area covers Indonesia’s land region, while for evaluating the impact of specific treatment over urban areas we used the AERONET data from Bandung, Pontianak, and Makassar sites. The comparison of AOD retrieved from modified BOD and the AERONET ground-based data showed that the corrected surface reflectance improved the accuracy of AOD in the three sites, with a correlation coefficient increased from 0.23 to 0.37 and the fraction of ‘good retrieval’ changed from 35% to 51%.

Keywords: Aerosol Optical Depth, clear-sky minimum reflectance, Himawari-8, AERONET

1. Introduction

The quantitative estimation of aerosol effects in climate change are still uncertain, despite their significant role in the Earth–Atmosphere–Ocean system [1]. To reduce this uncertainty, much more research on aerosols and their effect on climate is highly required. This includes the development of better methods to measure aerosol optical and its physical properties on local and global spatial scales. Aerosol optical depth (AOD) is one of the key parameters that must be accurately quantified.

The study will describe a retrieval method of aerosol properties over the land areas from Himawari-8 satellite data. Remote sensing of aerosols over land is important because the primary source of aerosols is derived from anthropogenic causes [2,3]. The retrieval of aerosol over land is also much more complicated than it is over the oceans because the land surface contribution is large and variable [2]. The study will take advantage of the higher temporal of geostationary satellite data, thus the high temporal variability of atmospheric aerosols in a region can be revealed.
AOD retrieval algorithm from remote sensing satellite has been developed for decades. The basic principle of the retrieval is the separation of the aerosol reflectance from the total reflectance detected by the satellite instrument, including reflectance from the surface and atmosphere. Aerosol retrieval is usually only worked for cloud-free situations. The estimation of surface reflectance remains the key parts and become a major source of error in AOD retrieval, since the reflectance from other components e.g., the Rayleigh scattering, can be calculated with high certainty.

One conventional method to estimate surface reflectance from geostationary satellite observation is by finding a clear-sky minimum reflectance from a duration [4]. The advantage of using geostationary data is that the ‘background image’ acquired from composed minimum reflectance values can be obtained from numerous views of the same location [5]. However, when the surface reflectance is calculated from the clear-sky minimum reflectance, background aerosol optical depth (BOD) is assumed to be closed to zero. This assumption generates larger surface reflectance, especially when the retrieval is performed over urban areas which leads to underestimation of AOD retrieved. This study aims to develop a retrieval algorithm of aerosol from Himawari-8 satellite and propose a correction for BOD value to be applied for AOD retrieval primary over urban areas where the pollution or natural source aerosol is persistent for the long term.

2. Data and area of study
The study area covers the regions over land area of Indonesia (-15°S – 10°N, 90°E – 145°E). The data period used in the study is April – September 2018. Himawari-8 data are obtained from P-tree System, Japan Aerospace Exploration Agency (JAXA), Earth Observation Research Center (EORC) (http://www.eorc.jaxa.jp/ptree/). The primary data needed for aerosol retrieval from Himawari-8 are the albedo/reflectance of blue (470nm) and red (640 nm) channels at the top of the atmosphere. The Himawari-8 level-2 cloud products are also utilized in the study to determine cloud-free pixel area. Spatial resolution for both albedo and cloud products is 5x5 km, with 10-minute interval temporal resolution. Due to the limit availability of the visible channels, the retrieval was only be performed for daytime data observation (00 – 06 UTC).

Determination of surface reflectance becomes one of the crucial parts of aerosol retrieval. For validation, surface reflectance from Himawari-8 was compared to MODIS surface reflectance product (MOD/MYD09). These data provide an estimate of the surface spectral reflectance as it would be measured at ground level in the absence of atmospheric scattering or absorption. In this study, the 8-days products (MOD/MYD09A1) are used, which are the best possible Level-2 observation during an 8-days period as selected based on high observation coverage, low view angle, the absence of clouds or cloud shadow, and aerosol loading.

AERONET is a globally dispersed network of automated ground-based sun/sky scanning radiometers, which provides correlative ground-based measurements for satellite and model validation studies at specific geographic locations [6]. Because of their relatively high AOD accuracy, AERONET data are widely used for validation of satellite retrievals and transport. In this study, AOD data (Level 1.5) from 3 AERONET sites (Bandung, Pontianak, and Makassar) are used to evaluate the BOD correction applied in the algorithm. The data are downloaded from http://aeronet.gsfc.nasa.gov/.

3. Methods
The flowchart for the AOD retrieval procedure is shown in Figure 1. The algorithm starts from data collection of the two visible channels (470 and 640 nm) of Himawari-8 reflectance. Clear-sky pixel selection was then applied by utilizing the JAXA cloud products, and the AOD will be retrieved only on that clear-sky pixels. Reflectance data were then converted to semi-surface reflectance \(A_{sfc}(\lambda)\) using calculations of look-up tables (LUT) from Santa Barbara DISORT Radiative Transfer (SBDART) code [7] assuming background aerosol condition. The term ‘semi surface reflectance’ is used to represent atmospheric corrected surface reflectance and to distinguish it with the ground true reflectance, which is determined as the 2nd minimum reflectance from 30 days composite. Aerosol reflectance \(R_{aer}(\lambda)\) was then estimated after separation from surface reflectance \(A_{sfc}(\lambda)\) and the contribution
from Rayleigh scattering ($R_{Ray} (\lambda)$). To retrieve AOD from $R_{aer} (\lambda)$, another set of LUT from SBDART have been precomputed in the offline process assuming five different types of aerosol models as proposed by OPAC [8].

The retrieval of AOD requires a radiative transfer model calculation which is a time-consuming process. To accelerate this process, the calculations are computed in advance and stored into the LUT. Since the TOA reflectance is most affected by the amount and microphysical properties of aerosol, the aerosol models assumed in the LUT should be well defined to obtain the AOD value accurately. A few aerosol models from the Optical Properties of Aerosols and Clouds (OPAC) [8] database, were used in this study. The formula used to calculate aerosol reflectance ($R_{aer} (\lambda)$) using SBDART model under dark surface condition (surface albedo = 0) is as follows [2]:

$$R_{aer}(\lambda, \theta_0, \theta_s, \varphi) = R_{TOA}(\lambda, \theta_0, \theta_s, \varphi) - R_{Ray}(\lambda, \theta_0, \theta_s, \varphi)$$

### Table 1. LUT dimensions for AOD retrievals used in the study calculated by SBDART code

| Variable      | No. of entries | Entries               |
|---------------|----------------|-----------------------|
| Wavelength ($\lambda$) | 2              | 470, 640 nm           |
| SZA ($\theta_0$)     | 8              | 0°~70° ($\Delta = 10°$) |
| VZA ($\theta_s$)     | 8              | 0°~70° ($\Delta = 10°$) |
| RAA ($\varphi$)      | 19             | 0°~180° ($\Delta = 10°$) |
| AOD ($\tau$)         | 9              | 0.0, 0.2, 0.4, 0.8, 1.0, 1.4, 1.8, 2.2, 3.0 |
| Aerosol Model       | 5              | Continental Clean (CC), Continental Average (CA), Continental Polluted (CP), Urban (Ur), Desert Dust (DD) |

### 3.1 Look-up Table (LUT) construction

The retrieval of AOD requires a radiative transfer model calculation which is a time-consuming process. To accelerate this process, the calculations are computed in advance and stored into the LUT. Since the TOA reflectance is most affected by the amount and microphysical properties of aerosol, the aerosol models assumed in the LUT should be well defined to obtain the AOD value accurately. A few aerosol models from the Optical Properties of Aerosols and Clouds (OPAC) [8] database, were used in this study. The formula used to calculate aerosol reflectance ($R_{aer} (\lambda)$) using SBDART model under dark surface condition (surface albedo = 0) is as follows [2]:
where, $R_{TOA}$, $R_{Ray}$ are the TOA and Rayleigh reflectance, respectively. $R_{Ray}$ can be obtained when aerosols do not exist ($AOD_{550} = 0$) [2]. $\theta_0$, $\theta_s$, and $\phi$ are sun zenith angle, satellite viewing angle, and relative azimuth angle between sun and satellite. Reflectance can be calculated by the normalization of radiance $L(\lambda)$ to the extraterrestrial irradiance $F_0(\lambda)$. Table 1 shows the dimension of LUT used in the study to convert the calculated aerosol reflectance to the AOD.

### 3.2. AOD retrieval

The retrieval of aerosol in this study includes aerosol optical depth at 550 nm ($AOD_{550}$) and single scattering albedo (SSA). The first step of this retrieval starts from reading the LUTs associated with specific solar and viewing geometry of observation data. In the second step, the algorithm selects one among five aerosol models that best matches the two visible channels observations simultaneously. The selection of aerosol model is based on the smallest relative residual ($RR$) calculated as:

$$RR = \left( \frac{R_{470}^{cal}(\tau)}{R_{470}^{obs}} - 1 \right)^2 + \left( \frac{R_{640}^{cal}(\tau)}{R_{640}^{obs}} - 1 \right)^2$$

where, $R_{i}^{obs}$ and $R_{i}^{cal}$ are the observed and calculated reflectances in channel $i$, respectively, and $\tau$ is AOD at 550 nm.

Once the best match aerosol model has been selected for every pixel of observation data, the algorithm will perform another selection to obtain the most appropriate model of single scattering albedo. In this case, additional LUTs were calculated for each aerosol model by changing (increasing and lowering) the SSA value ($\Delta SSA = 0.005$). This step is required in order to minimize errors in selecting the aerosol model as well as to generate SSA estimation. In the final step, the satellite observed aerosol reflectance was converted to the hypothetical $AOD_{550}$ for each pixel based on geometry and selected aerosol model LUT. This principle is illustrated in Figure 2, where the aerosol reflectance in the red (640 nm) channel is plotted as a function of the aerosol reflectance in the blue (470 nm) channel. For simplicity, Figure 2 plots the reflectances from the LUT for two aerosol models (models 1 and 2) only.

![Image](image_url)

**Figure 2.** Illustration of simultaneous retrieval of aerosol optical depth and aerosol model from two channels. Step (1): It is known that relative residual of model 1 is the smallest, thus model 1 is selected by the algorithm. Step (2): Another selection is performed to find a model that best matched the observation by changing the SSA value of model 1. AOD will be retrieved from this final selected SSA model.

### 3.3. BOD Correction

The default value of background aerosol optical depth (BOD) is assumed to be 0.02. This assumption can be applied in the region where the pollution or natural source aerosol is not persistent for a long term [9]. The retrieved surface reflectance from TOA reflectance that does not consider the actual BOD...
will contain errors in the calculation. Underestimation of BOD will generate larger surface reflectance, since scattering component due to the background aerosol still remains. This overestimated surface reflectance will reduce the difference between the total reflectance at TOA and at surface, that leads to smaller AOD retrieved.

In the algorithm, modification is applied for the cases of retrieval over urban areas. Specific BOD values will be used based on the average value of 30-days minimum AOD from selected sites of AERONET. Also, for these specific areas, AOD retrieval will also only used the urban type aerosol model LUT. The separation of urban areas from other regions was performed by utilizing information from MODIS land cover data product (MCD12Q1) shown in Figure 3.

![Figure 3. Land cover type over Indonesia land area obtained from MODIS product (MCD12Q1) 2013. Some similar types of landcover have been merged for simplification. The red color indicates urban and built-up area where specific case treatment in AOD retrieval will be applied.](image)

**4. Results and Discussion**

**4.1. Surface Reflectance Retrieval**

Indonesia is recognized as a unique and complicated ocean–atmosphere–land environment for studying both the climatic effects and air pollution due to aerosol particles [10,11]. Performing remote sensing of aerosol over this region is also challenging. One of the reasons is because of its high cloud coverage. The monthly average cloud cover in Indonesia is more than 60% [10], which made the number of AOD derived in the region were limited. Moreover, thin cirrus, which is ubiquitous over Indonesia [11], often cannot be separated well in the aerosol retrieval algorithm. Certainly, contamination of clouds possibly causes larger errors in generating surface reflectance that tends to make it overestimate.

![Figure 4. The difference of Himawari-8 2nd-minimum reflectance and MODIS surface reflectance product at 470 nm and 640 nm during April 2018.](image)
Comparisons between Himawari-8 and MOD09 surface reflectance over Indonesia’s land area are shown in Figure 4. Unlike Himawari-8, where its surface albedo was generated from the 2nd minimum composite, surface reflectance from MODIS in the comparison was obtained from averaging every data available within the same period. MODIS has smaller number of observation than Himawari-8 due to their lower temporal resolution. However, the figure still indicates some good agreements. The average difference of surface reflectance from Himawari-8 and MODIS, as shown in Figure 4, are +0.067 and +0.029 for 470nm and 640 nm channels respectively. The spatial distribution shown by both satellite images were slightly similar. Higher reflectance values (more than 0.20) were found along the center of Papua Island (east side of Indonesia), where mountainous peaks are located. These areas are sometimes covered by snow which makes the pixels brighter. Another possibility is, since orographic clouds are very intense produced over the mountainous area, the clear sky observations were never been obtained, so the pixels generated were still contaminated by clouds.

4.2. AOD retrieval
The average of AOD retrieved from Himawari-8 over Indonesia region is shown in Figure 5 (left). Spatially, the monthly AOD distribution was not changed significantly from April to September. Higher AOD values, ranging from 0.18 to 0.52 (mean = 0.35), were distributed over the western area i.e., at Sumatra Island and Java Island where most Indonesia’s population live. More minor concentration of aerosols was found mainly over the eastern area i.e., at Papua and Sulawesi Island. Since the region’s land cover are dominated by mountainous forest, the AOD values retrieved are reasonable which range from 0.02 to 0.38 (mean= 0.23).

Some differences appeared when the result compared to MODIS AOD (Figure 5 (right)). Unlike Himawari-8 AOD, in MODIS, higher aerosol loading was only concentrated over Java Island. There were two cases when other areas have higher AOD values than Java i.e., in April over northern side of Sumatra and in September over the western side of Kalimantan Island. AOD values in MODIS were also broader than that of Himawari-8, which range from 0.01 to 0.83. AOD showed by MODIS also indicated clear disparity between urban/developed areas (mostly in Java) and rural/vegetated areas (other areas than Java). Some AOD were failed to be retrieved in MODIS, mainly over Papua Island. This is possibly because MODIS algorithm used stricter clear-sky pixel selections than that of Himawari-8 in this study.

4.3. Specific case for urban areas
The improvement of aerosol retrieval over the urban areas was made by two specific treatments. First, the only aerosol model type used to generate the LUT is urban aerosol, which is different from other land types that let the algorithm select the best-matched aerosol model. Second, the correction of background aerosol optical depth was performed only for urban areas. The BOD over these areas was expected higher than the default value since their relatively larger amount of high absorption aerosol loaded by human activities, which usually persists for a long term, than rural or vegetated areas. The calculation of BOD over urban areas is based on the average 30-days minimum value of AOD. Since
ground-based observation for aerosol measurement in Indonesia is very limited, the data used for determining the BOD is taken from MODIS aerosol level-2 product.

Table 2. Summary of the AOD validation result over several urban areas

| Site    | Default BOD (0.02) | Modified BOD |     |     |     |
|---------|--------------------|--------------|-----|-----|-----|
|         | r      | r^2  | RMSE | Gfrac | r    | r^2  | RMSE | Gfrac |
| Bandung | 0.19   | 0.03 | 0.044| 0.43  | 0.40 | 0.16 | 0.023| 0.66  |
| Pontianak | 0.24  | 0.06 | 0.053| 0.29  | 0.46 | 0.21 | 0.028| 0.46  |
| Makassar | 0.25  | 0.06 | 0.045| 0.33  | 0.26 | 0.07 | 0.037| 0.42  |
| Average | 0.23  | 0.05 | 0.05 | 0.35  | 0.37 | 0.15 | 0.03 | 0.51  |

The in-situ aerosol observation from AERONET was used for validation. However, due to a lot of missing data found on the other sites within the study period, the validation only was performed at Bandung, Pontianak, and Makassar. Scatter plots of AOD-550nm retrieved from Himawari-8 and ground-based AERONET are shown in Figure 6. In the figures, blue-dashed line indicates its linear trend, and black-dashed lines are the tolerance error interval. The data plots that fall within this interval indicated as good accuracy retrieval, and G_frac is the percentage of good retrieval to the total amount of data.

![Figure 6](image_url)

Figure 6. Scatter plot of AOD-550nm retrieved from Himawari-8 (y-axis) and ground-based AERONET AOD-550nm (x-axis) retrieved from default BOD and modified BOD in Bandung, Pontianak, and Makassar during April – September 2018.

Table 2. shows the summary of the validation result. The accuracy of the retrieval obtained from 3 sites average is about 51%. Moderate accuracy retrieval was yielded (G_frac= 0.66) at Bandung. However, its correlation was relatively poor (r = 0.40). At Makassar, the AOD retrieved were not well correlated to AERONET (r = 0.26). In this site, the retrieval accuracy was also the least compared to the others (G_frac= 0.42, RMSE = 0.037). The highest correlation (r = 0.46) was found at Pontianak, but
the fraction of good retrieval over this site was only 46%. The specific urban type treatment was applied in the algorithm for these three sites. The treatment effect can be seen as higher AOD retrieved from modified-BOD than that of the default. This correction of BOD calculation generated lower surface reflectance and reduced underestimation of AOD retrieved over urban areas.

5. Conclusion
The development of an aerosol retrieval algorithm has been presented in this study which used two visible channels (470 nm and 640 nm) of the geostationary satellite Himawari-8, over the land area of Indonesia. The specific treatment for urban areas i.e., urban type used for LUT and correction of BOD were applied for urban land areas to improve the retrieved AOD.

In general, the AOD algorithm used in this study could generate acceptable result, based on its comparison with the aerosol product from MODIS. Spatial distribution of monthly average aerosol retrieved by Himawari-8 was similar to that of MODIS. The accuracy of AOD retrieval, calculated by averaging G_frac values from all of the ground-based sites used, was about 51%. The impact of background optical depth modification can be seen in Bandung, Pontianak, and Makassar. AOD retrieved over these urban areas generated higher AOD.

The AOD retrieval over Indonesia land is challenging because the region is highly covered by cloud, mainly thin cirrus which sometimes cannot be distinguished from the total reflectance detected by satellite. The use of advance cloud masking algorithm that covers thin cirrus detection is expected to overcome this issue. Moreover, the difficulty in AOD retrieval is also caused by a very limited number of ground-based aerosol observations, which is required to characterize the aerosol properties.

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