Aerosol retrieval algorithm for the characterization of local aerosol using MODIS L1B data

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Abstract. Atmospheric aerosol plays an important role in radiation budget, climate change, hydrology and visibility. However, it has immense effect on the air quality, especially in densely populated areas where high concentration of aerosol is associated with premature death and the decrease of life expectancy. Therefore, an accurate estimation of aerosol with spatial distribution is essential, and satellite data has increasingly been used to estimate aerosol optical depth (AOD). Aerosol product (AOD) from Moderate Resolution Imaging Spectroradiometer (MODIS) data is available at global scale but problems arise due to low spatial resolution, time-lag availability of AOD product as well as the use of generalized aerosol models in retrieval algorithm instead of local aerosol models. This study focuses on the aerosol retrieval algorithm for the characterization of local aerosol in Hong Kong for a long period of time (2006-2011) using high spatial resolution MODIS level 1B data (500m resolution) and taking into account the local aerosol models. Two methods (dark dense vegetation and MODIS land surface reflectance product) were used for the estimation of the surface reflectance over land and Santa Barbara DISORT Radiative Transfer (SBDART) code was used to construct LUTs for calculating the aerosol reflectance as a function of AOD. Results indicate that AOD can be estimated at the local scale from high resolution MODIS data, and the obtained accuracy (ca. 87%) is very much comparable with the accuracy obtained from other studies (80%-95%) for AOD estimation.

1. Introduction

Atmospheric aerosol plays an essential role in solar radiation budget, climate change, hydrology process, air quality and visibility through the scattering and absorption of incoming solar energy [1]. The major sources of aerosol are; i) natural sources (dust, volcanic, sea-salt) and ii) anthropogenic sources (human-made activity) [2], and it can be composed by two categories such as primary aerosols and secondary aerosols. The size of aerosols varies and can be classified into two size groups i.e. particulate matter 2.5 (PM 2.5) and particulate matter 10 (PM 10). PM 2.5 is also called fine mode refers to the particles of aerosol with the diameter of less than 2.5 micrometer, while PM 10 is called coarse mode which describes particles with the diameter less than 10 micrometer. Aerosol optical depth (AOD) and Angstrom coefficient are two important parameters in measuring aerosol retrieval. The AOD retrieval requires high spatial and temporal resolution of data because of the short life span of aerosol (7 to 10 days) [3]. However, the key factor on the aerosol retrieval is estimation of surface

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reflectance that attempts to differentiate the aerosol signal from surface [4]. There is complexity in measurement of aerosol retrieval over land compared with the ocean. This complexity occurs due to the surface reflectance over land is higher and varies spatially and temporally [5]. Although this problem is the most challenging part for aerosol retrieval over land compared to ocean, the measurement of accurate surface reflectance over land is necessary to monitor the sources of aerosol over land, because an inaccurate estimation of 0.01 results in an uncertainty of 10% in AOD estimation [4].

The direct retrieval of aerosol from remote sensing data is complex, time consuming and required lots of computation especially for the construction of LUTs using RTM code. The advantages of the use LUTs for retrieval of the AOD are; accurate retrieval procedures, realistic atmospheric models, accurate radiative transfer computations, and ensure fast processing of satellite data [6]. Previously, RTM code was difficult to handle, however, lot of improvement have been done lately to make user-friendly interfaces for RTM codes [7]. Nevertheless, the LUTs techniques still facing some difficulties and the limitation of LUTs can be seen on the computation of the LUTs based on huge bulk of previously computed data which required recomputation every time the atmospheric model is changed [6].

Many studies have conducted for the retrieval of AOD at local level using different types of remote sensing data and different techniques [8]; [5]; [9] and all of these retrieval models have advantages and disadvantages in context of data, retrieval techniques and aerosol model used in the RTM codes. Aerosol product (AOD) from MODIS data is also available to monitor aerosol distribution at global and local scale. The main problem is that the aerosol product can provide reasonable accuracy for monitoring the characteristics of the global aerosol but the accuracy for the local aerosol distribution and the data is not really satisfactory because the estimation of aerosol at local level with high accuracy requires high spatial resolution data and local aerosol model needs to be considered during the LUTs construction which is not possible for the product of global aerosol. Therefore, the main purpose of this study is to estimate aerosol over land especially in urban areas in Hong Kong for a long period of time (2006-2011) using high resolution MODIS L1B data (500 m) and local aerosol model. Local aerosol model was developed based on a set of parameter from AERONET inversion product level 2, and two types of surface reflectance were used i.e. i) surface reflectance using dark dense vegetation (DDV) and surface reflectance from MODIS atmospherically product.

2. Study Area and data used

The study area of this research is Hong Kong which is situated on south coast of China, and has been known as one of the most densely populated areas in the world. Data from MODIS Terra satellite such as MOD02HKM, MOD03 and MOD09GA) were used for the main processing. MOD02HKM is swath data with calibrated radiance at 500m. MOD03 is geolocation data which contains geodetic coordinates, ground elevation, solar zenith angle, solar azimuth angle, satellite zenith angle and satellite azimuth angle. MOD09GA is land surface reflectance product at 500m. Additionally, MODIS aerosol level 2 collection 005 (MOD04 L2 C005) was used to compare with our result. However, apart from the satellite data, AERONET Level 1.5 data was used for the validation.
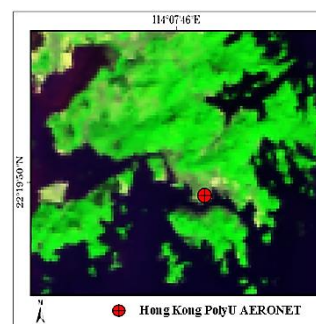

Figure 1. Study area and Hong Kong PolyU

3. Methodology

The total methodology for the aerosol retrieval algorithm is very complex and composed of many different steps of image processing techniques. However, in short the methodological consideration can be divided into three parts i.e. i) estimation of aerosol reflectance from MODIS data which has been done by estimating TOA reflectance, Rayleigh reflectance and Surface reflectance, ii) estimation of aerosol reflectance as a function of AOD has been carried out by creating a LUTs using SBDART

code considering local aerosol models, different sun and satellite geometries and hypothetical AOD values, and iii) finally AOD from MODIS data was estimated by using an optimal spectral fitting. The overall methodology is presented in Figure 2, but a shore description of the main processing steps is presented in the following subsections.

3.1. Aerosol Reflectance from MODIS

The retrieval of aerosol reflectance from MODIS is consisted of three main steps as follows, beside there are few preprocessing steps are involved for the total satellite image processing.

Figure 2. Workflow of AOD retrieval using MODIS L1B data

3.1.1. TOA reflectance from MODIS. After the pre-processing (geo-referencing, bow tie correction, subset, and water and cloud masking) of satellite data, satellite receives TOA spectral radiance $_{TOA(\lambda)}$ was normalized to the solar illumination condition for each wavelength to generate TOA spectral radiance [11] using the equation (1) as follows: $\rho_{TOA(\lambda)} = \frac{\pi L_{TOA(\lambda)}}{E_0 cos\theta_s}$ (1), *where, E_0 is extraterrestrial solar irradiance, and θ_s is solar zenith angle.*

3.1.2. Rayleigh reflectance estimation. Estimation of Rayleigh reflectance ($P_{Ray}(\lambda)$) was carried out (equation 2) by calculating Rayleigh optical depth [12] and Rayleigh Phase Function [13]. $P_{Ray}(\lambda) = \frac{\tau_{Ray}(\lambda).\rho_{Ray}}{4(cos\theta_s.cos\theta_v)}$ (2), *where $\tau_{Ray}(\lambda)$ is Rayleigh optical depth, ρ_{Ray} is Rayleigh phase function, $cos\theta_s$ is cosine solar zenith angle, and $cos\theta_v$ is cosine sensor zenith angle.*

3.1.3. Estimation of Surface Reflectance. Surface reflectance measurement is most crucial and complex part when performing the aerosol retrieval from remote sensing data [10]. In this study, estimating surface reflectance was done using direct technique and DDV technique. For direct technique, surface reflectance was taken directly from MODIS land surface reflectance product (MOD09GA) for 0.66 wavelength (band 1) and 0.47 wavelength (band 3) because this data has already been calibrated by refining atmospheric correction algorithm [14]. On the other hand, DDV technique is based on a stable relationship between surface reflectance in the short-wave infrared (SWIR) in 2.12 μm wavelength and reflectance in the 0.47 μm and 0.66 μm wavelengths [15].

3.2. Aerosol retrieval based on RTM and LUTs

Santa Barbara DISORT Radiative Transfer (SBDART) code was used to construct LUTs for calculating the aerosol reflectance as a function of AOD [7]. Several inputs were required to generate LUTs using the SBDART code such as AOD at 0.55 μm, spectral aerosol extinction, single scattering albedo (SSA), and asymmetry factor (g) [2]. Local aerosol model parameterization was carried out using K-means clustering analysis of 23 parameters of AERONET level 2 inversion products which include angstrom coefficient, SSA at 4 wavelengths, real and imaginary refractive index at the same 4 wavelengths, g, mean radii, standard deviation and total volumes of the coarse and fine mode particles. LUTs were constructed by combining AOD at 0.55 μm (0.0, 0.2, 0.4, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.5), 2 bands (0.47 μm and 0.66 μm), 4 aerosol models, 9 solar zenith angles (0º ~ 80º, Δ=10º), 17 of view zenith angles (0º ~ 80 º, Δ=5º), and 18 relative azimuth angles (0º ~ 170º, Δ=10º). From the LUTs, aerosol reflectance was derived by separating Rayleigh reflectance (TOA reflectance, when AOD is zero) from TOA reflectance.

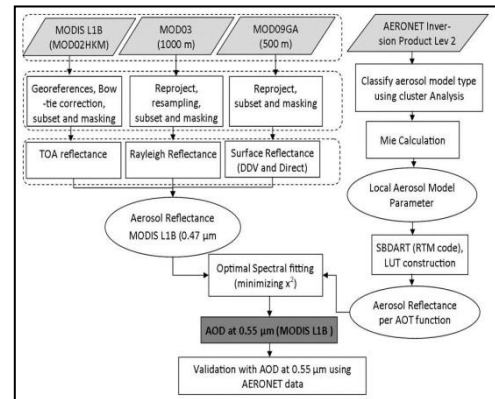### 3.3. AOD at 0.55 μm using MODIS

AOD at 0.47 μm and 0.66 μm wavelength was derived by conducting the comparison between aerosol reflectance from MODIS with aerosol reflectance from each geometrically corrected LUTs. The comparison was done by using an optimal spectral shape-fitting technique in order to select the aerosol model with the smallest systematic errors [5]. The minimum residual of x^2, was selected from all aerosol types for each pixel and the best local aerosol model was used to produce AOD image. Finally AOD at 0.55 μm was extracted using the relationships between wavelength and Angstrom coefficient [16].

3.4. Results of aerosol retrieval

Aerosol retrieval has been done for 115 days from 2006 to 2011 using the land surface reflectance from DDV and direct technique. Overall, it was found that all AOD maps using the direct technique showed a very good spatial distribution of local aerosol pattern compared to the other methods. For example, Figure 3a and 3b show the spatial distribution of AOD retrieved from MODIS L1B using direct technique and AOD from MOD04 L2 C005 over Hong Kong region. It is obvious from the Figure 3a that AOD map retrieved from MODIS L1B can show spatial distribution of local AOD very clearly, while very poor spatial distribution of AOD can be seen from the MOD04 L2 C005 AOD map because of the low resolution. Moreover, it is also commonly observed that AOD values for many pixels are missing from the MOD04 L2 C005 AOD map and sometimes this problem was occurred over the particular region especially on urban and polluted areas. Therefore, it can be said that the AOD retrieved from MODIS L1B is more reasonable due to higher spatial resolution data (500 m) that helped to estimate AOD in more details.
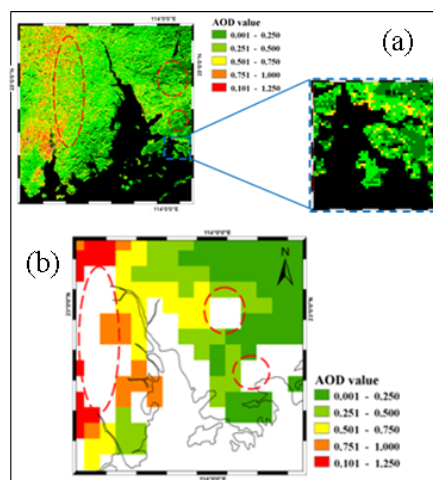

Figure 3. (a) MODIS L1B AOD map using direct technique and (b) MOD04 L2 C005 AOD map

3.5. Validation of aerosol retrieval

The validation of the results was performed by the statistical modelling between the AOD retrieved from the MODIS L1B and the AOD collected from the AERONET station at the Hong Kong Polytechnic University site over the six years (2006-2011). For the statistical modelling, an averaging of MODIS L1B AOD was performed using an averaging area of interested mask (AOI) of 9 by 9 pixels. While an averaging of AOD value within ± 30 minutes of MODIS overpass time was performed for AERONET data. The accuracy of the of the validation was determined based on the commonly used statistical measurements such as correlation coefficient (r), correlation of determinant (r^2), and root mean square error (RMSE).

The validation results (table 1) showed a good agreement between AOD from MODIS L1B (using direct land surface reflectance and using DDV technique) with AERONET data. However, it is worthwhile to mention that for every year a better agreement between MODIS AOD and AERONET AOD was obtained using land surface reflectance directly in the aerosol estimation algorithm. The highest validation accuracy (r=0.91 and RMSE=0.21) was achieved for the year 2006 and 2011 using the direct land surface reflectance,

Table 1. Comparison of AOD MODIS L1B using DDV and direct with AOD AERONET for the year 2006 and 2011

Year	DDV			Direct land surface reflectance		
	r	r^2	RMSE	r	r^2	RMSE
2006	0.80	0.64	0.44	0.91	0.83	0.21
2007	0.83	0.69	0.34	0.89	0.79	0.15
2008	0.89	0.77	0.44	0.91	0.82	0.23
2009	0.84	0.70	0.36	0.88	0.77	0.16
2010	0.71	0.50	0.41	0.88	0.77	0.19
2011	0.82	0.67	0.29	0.85	0.71	0.16

while the lowest validation accuracy (r=0.71 and RMSE=0.41) was found for the year 2010 using the land surface reflectance from the DDV technique. Validation was also performed using all the data (115 days from 6 years) together. Results (Figure 4) also indicated a good agreement between

MODIS AOD and AERONET AOD, however, similar to the individual year, the highest validation accuracy (r=87, RMSE=0.186) was obtained using land surface reflectance directly in the aerosol estimation algorithm. This overall situation indicated that aerosol estimation can be made using MODIS L1B 500m data very reasonable accuracy but a better accuracy can be obtained if land surface reflectance (MOD09GA) was used in the retrieval algorithm.

In this validation process, a comparison was also made between AOD retrieved from MODIS L1B data and AOD from MOD04 L2 C005 collection (10 km resolution) in order to examine whether AOD from this higher resolution (500m resolution) MODIS L1B data has a good correlation with the global AOD product (MOD04 L2 C005 collection) or not. However, it is necessary to mention here that MOD04 L2 C005 collection is not available for all days (115 days) like we used for this research, so we only used 48 days AOD MOD04 L2 C005 collection for this comparison. From the comparison, it is very most obvious that AOD retrieved from MOD04 L2 C005 (10 km resolution) show good agreement (r = 0.96 and RMSE= 0.008) (Figure 5a) with the AOD retrieved from AERONET, while with similar points (similar days), the correlation between AOD retrieved from MODIS L1B (using direct technique) with AOD retrieved from AERONET data is 0.86 and RMSE is 0.125 (Figure 5b). The accuracy obtained from the MOD04 L2 C005 collection is comparatively higher (r=0.96) but considering the spatial distribution of local aerosol (Figure 3a), the AOD retrieved from the MODIS L1B is still useful to understand the spatial distribution of local aerosol with the accuracy (r) of 0.86.

Figure 4. Comparison of AOD MODIS L1B using (a) DDV and (b) Direct with AOD AERONET

Figure 5. Comparison of (a) AOD MOD04 L2 C005, and (b) AOD MODIS L1B Direct with AOD AERONET

4. Discussion and conclusion

This study discussed on the retrieval of AOD at 0.55 μm using MODIS L1B data by characterization of local aerosol model. Two different technique for estimating surface reflectance (DDV and direct) were used in this study and SBDART code was used to construct LUTs based on aerosol parameters. Validation was performed using AERONET data. The AOD retrieved using direct land surface reflectance (MOD09GA) gives more accurate result than AOD derived using DDV technique. The probable reason for this higher accuracy using MOD09GA is that this land surface reflectance estimated using rigorous atmospheric correction based on vector radiative transfer (6SV) code which is usable for aerosol retrieval for vegetated surface as well as bright urban surface [17]. On the other hand, estimation of surface reflectance using DDV technique is not suitable for bright urban surface areas which have a high surface reflectance. The DDV technique works only for areas which has a low surface reflectance and requires more than 60% coverage of vegetation area [9]. AOD retrieved from MOD04 L2 C005 has high accuracy due to the resolution of MOD04 L2 C005 is 10 km and it's has 20 times higher signal to noise ratio compared to AOD retrieved from MODIS L1B data (500 m resolution) [1].However, the problem is for AOD MOD04 L2 C005 is that not only the spatial resolution is poor but the data also is not available in near real-time. Instead that, AOD retrieved from MODIS L1B data is more suitable to be used because of high spatial resolution data that can estimate AOD in more details with near to real-time observation.
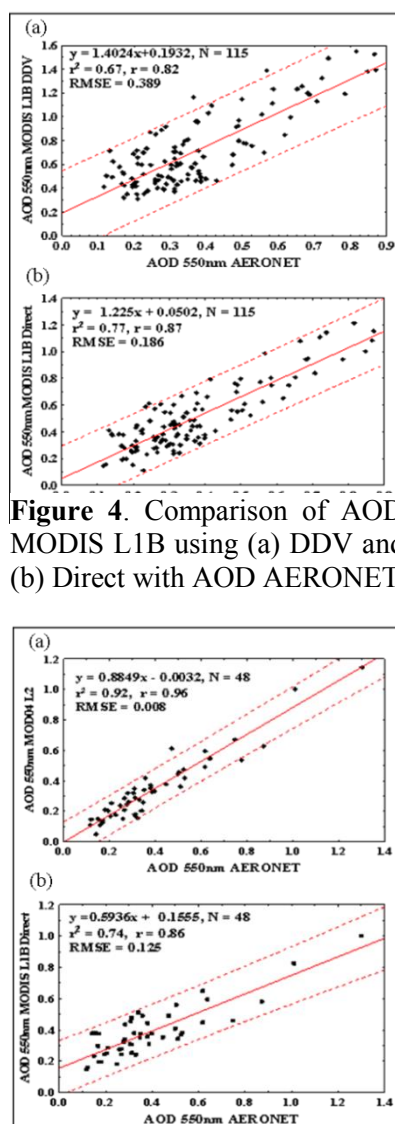
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