Remote Sensing of Environment 181 (2016) 1–13

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

A parameterization scheme of aerosol vertical distribution for surface-level visibility retrieval from satellite remote sensing

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ARTICLE INFO

Article history:
Received 26 February 2015
Received in revised form 9 March 2016
Accepted 18 March 2016
Available online xxxx

Keywords:
Visibility
Satellite
Parameterization
Aerosol

ABSTRACT

In this study, a vertical correction method based on a two-layer aerosol model is proposed to estimate the surface-level visibility from satellite measurements of aerosol optical depth (AOD). The meteorological parameters from the re-analysis data of the National Centers for Environmental Prediction (NCEP) are applied to estimate the aerosol layer height (ALH) of the two-layer aerosol model via an automatic workflow. The estimated extinction coefficients near the surface by AOD/ALH over the single point of a lidar site in Shanghai agree well with those of the ground measurements from a visibility sensor, with a correlation coefficient of 0.86 and root mean squared error (RMS) of 0.19 km^{-1} for the data set from April 18, 2008 to April 30, 2014. The season-long spatial comparison demonstrates that most of the correlation coefficients (90%) are >0.6, and more than half of the samples (68%) have coefficients higher than 0.7 for the data set from January 1 to April 30, 2014. Dust transportation and higher relative humidity (RH) have been confirmed to be important factors in reducing the accuracy of estimated visibility, as these situations fail to meet the assumptions of the two-layer model. Additionally, the less-rigorous cloud mask algorithm of the Moderate Resolution Imaging Spectroradiometer (MODIS)/AOD might lead to overestimates of AOD, and further underestimating of the surface-level visibility. The spatial variation of temporal correlation coefficients shows that most comparison sites (>74%) of satellite estimations agree well with the surface-level visibility measurements, with correlation coefficients up to 0.6 during the study period. The northern area of Eastern China presented better agreement than the southern area. This may be related to the complex underlying surface characteristics and higher RH in the southern part. This work will significantly improve the quality of climate simulations and air quality forecasts in Eastern China.

1. Introduction

Aerosol significantly affects atmospheric visibility (Christopher, Kliche, Chou, & Welch, 1996) and human health (Li et al., 2005). For these reasons, aerosol has attracted extensive attention from scientists and decision makers throughout the world. Data of global ground-level visibility are not always available because of the limited number of locations with monitoring stations. Moreover, data of visibility in regions with rapid population growth is not always retrievable, and these regions are often the locations with significant recent air pollution. Satellite-based aerosol remote sensing with wide spatial coverage could provide useful information for various types of studies. This data could be especially useful for designing air quality control strategies, air quality forecasting, and epidemiological studies. Therefore, satellite measurement represents a beneficial supplement to the conventional measurements that are routinely used (Al-Saadi et al., 2005).

Aerosol optical depth (AOD), defined as the integrated extinction coefficients in the vertical direction for the entire atmospheric column, can be obtained from satellite remote sensing. The extinction coefficient near the surface is inversely proportional to visibility, with a Koschmieder quotient of 3.912 (Koschmieder, 1925). Therefore, the vertical distribution of aerosol is the most important factor in determining surface measurements of visibility from satellite-derived AOD (Engel-Cox, Martin, & Park, 2006). Moreover, aerosol vertical distribution is important for the assessment of aerosol radiative effects (both direct and indirect) on thermal structure and atmospheric stability (Satheesh et al., 2009). A recent study showed that space-borne AOD retrieval suffered from errors in assumptions regarding aerosol profile shapes (Rozwadowska, 2007). Ramanathan, Crutzen, Kiehl, and Rosenfeld (2001) showed that the formation and lifetime of a cloud can be affected by the vertical profile of absorbing aerosols. Meanwhile, the vertical distribution of absorbing aerosols also alters the reflectance

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http://dx.doi.org/10.1016/j.rse.2016.03.016

of the ocean-atmosphere system. Simulations of reflectance at the top of the atmosphere with distinct aerosol vertical distributions may lead to approximately 10% or even 20% relative differences, depending on aerosol absorption. In atmospheric correction algorithms, the differences are directly translated into errors on the retrieved water reflectance (Duforêt, Frouin, & Dubuisson, 2007).

Because the vertical distribution of aerosols is critical for assessing visibility, several techniques have been developed to evaluate it, among which lidar is the most popular. However, both space-borne lidar (e.g., the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite, and the Geoscience Laser Altimeter System (GLAS)) and ground-based lidar have limited spatial footprints and do not produce global daily coverage. The Medium Resolution Imaging Spectrometer (MERIS) and the new version of the Polarization and Directionality of Earth's Reflectances (POLDER) instrument, aboard the Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL) microsatellite, can provide better spatial coverage than laser-based systems. Oxygen absorption can be estimated from space by POLDER's or MERIS' measurements. With oxygen *A* band absorption, the altitude of aerosol layer over dark surfaces can be estimated if the model, optical thickness, and observation geometry of aerosol are known (Bréon & Bouffiès, 1996; Diedenhoven, Hasekamp, & Aben, 2005). However, the technique only provides one piece of information about aerosol altitude and is not applicable to bright surfaces (over land or under sunglint conditions), due to most of the signal at the Top of Atmosphere (TOA) coming from the surface in this case (Duforêt et al., 2007). Another technique is to obtain the column-integrated satellite AOD, and distribute it vertically on the basis of model-predicted aerosol distributions (e.g., Liu, Sarnat, Kilaru, Jacob, & Koutrakis, 2005; van Donkelaar, Martin, & Park, 2006; Kondragunta et al., 2008; Choi, Park, & Ho, 2009). This assumes that the physics, chemistry, radiation, and mechanics of the Planet Boundary Layer (PBL) height characterization are all correct in the model (Newchurch et al., 2008).

Therefore, there is a need for development of a new method to characterize the aerosol vertical distribution. The best approach to obtain gridded aerosol vertical distribution is to build parameterization schemes to describe it. For simplicity's sake, current parameterization schemes of aerosol vertical distribution often assume that aerosols are either all concentrated below the PBL (Liu et al., 2005; Koelemeijer, Homan, & Matthijsen, 2006; Al-Saadi et al., 2008), or that their concentration vertically decreases following an exponential law with a typical aerosol scale height (Wu et al., 2009; He, Deng, et al., 2010). This method is not appropriate for some situations, particularly for characterizing dust transportation or a residual layer (Gordon, 1997; Zhang et al., 2006; Han, Fang, Zhao, & Kang, 2008; He, Li, Mao, Lau, & Chu, 2008; Chen et al., 2009). Consequently, using a fixed distribution, even if it incorporates seasonal and monthly variation, may result in large errors on the surface-level visibility retrieval. He et al. (2008) addressed a two-layer aerosol model that included a lower layer of uniform aerosol extinction and an upper layer of aerosol extinction that decreased exponentially with height. This model exhibited better estimates of the extinction coefficient at the surface than those derived via a single layer model. In their study, the PBL height and the aerosol layer height (ALH) of the two-layer aerosol model were derived using lidar measurements. It is important to obtain these two parameters in each grid corresponding to the spatial resolution of satellite remote sensing, but a limited number of lidars in the region of interest cannot meet this requirement. Numerical models, such as the Weather Research and Forecasting (WRF) model, can predict PBL height at an acceptable accuracy (Eder et al., 2009), but it is impossible to present the ALH via the traditional meteorological numerical models. Meteorological conditions have also been found to be a major factor affecting vertical distributions of aerosols. The upper bound of the aerosol region is associated with strong inversions due to subsidence. Zhang, Ma, Tie, Huang, and Zhao (2009) found that meteorological conditions could strongly affect the vertical distribution of aerosol particles, and defined three types of aerosol with vertical distributions corresponding to different weather systems.

In this study, we apply meteorological parameters from NCEP reanalysis data to estimate the ALH of the two-layer aerosol model over a lidar observation site. We then extend this method to other regions without lidar observation to validate the accuracy of the estimated ALH. In Section 2, we briefly describe the measurements and methodology used for deriving the PBL height, ALH, and surface level visibility. In Section 3, the results and findings from the season-long measurements are discussed in detail, and the NCEP-derived aerosol vertical distributions are related for different regions. The results are summarized in Section 4.

2. Measurements and methodology

2.1. Micro pulse lidar

An MPL (MPL-4B, Sigma Space Corporation, United States) was operated at the Pudong Meteorological Bureau (31°14′ N, 121°32′ E; elevation = 14 m a.s.l) in Shanghai. Fig. 1 shows the location of the observation equipment. The observation site is located near a city street and exhibits typical urban surface characteristics.

The MPL measurements used in this paper have continuous coverage from April 18, 2008 to April 30, 2014, except for a period of system maintenance from July 6, 2011 to March 23, 2012. The MPL is a backscatter lidar that uses an Nd:YLF laser with an output power of 12 μJ at 532 nm and a 2500 Hz repetition rate. The vertical resolution of the lidar data is 30 m, and the integration time of the data is 30 s. The zone of incomplete afterpulse correction was approximately 130 m. MPL signals were averaged every 60 min to improve the signal-to-noise ratio for deriving aerosol extinction profiles, since most sharp changes of aerosol profiles in vertical variation were removed by averaging. On the basis of the hourly lidar extinction profiles, the measurements taken at 11:00 (LST) under cloud-free conditions were selected, for which there was either a well-mixed aerosol in PBL or an aerosol layer with monotonic decreasing extinction coefficients above PBL that resulted in the disappearance of the residual layer as far as possible

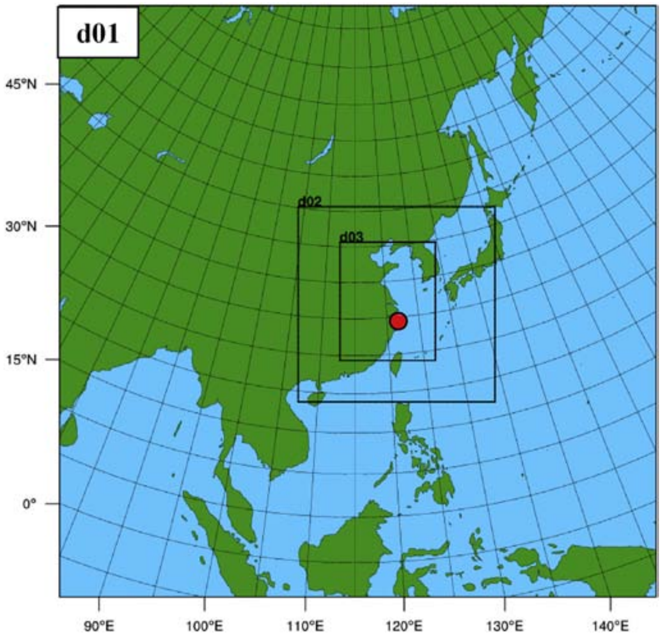

Fig. 1. Location of the lidar observation site and the coverage of the three model domains.