Atmospheric Pollution Research xxx (2016) 1–8

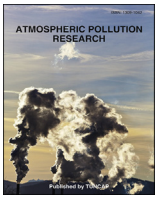
HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

Atmospheric Pollution Research

journal homepage: http://www.journals.elsevier.com/locate/apr



Original Article

Landsat 8-based inversion methods for aerosol optical depths in the Beijing area

Yang Ou [a], Fantao Chen [a], Wenji Zhao [a, *], Xing Yan [b], Qianzhong Zhang [a]

[a] *College of Resource Environment and Tourism, Capital Normal University, BJ 100048, China*
[b] *Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Hong Kong*

ARTICLE INFO

Article history:
Received 21 March 2016
Received in revised form
16 September 2016
Accepted 18 September 2016
Available online xxx

Keywords:
Beijing
Landsat-8 satellite
Aerosol
6S
MODIS Dark Target Method

ABSTRACT

As an essential component of the Earth-atmosphere system, aerosols have important impacts on the atmospheric environment and human health. Based on the data sourced from Landsat 8 satellite images, the goal of this paper is to retrieve aerosol optical depth (AOD) in the Beijing area by means of the MODIS Dark Target (DT) Method and the visible near-infrared (VNIR) atmospheric correction method (ACM), of which the accuracy is verified by observation data from AERONET. Furthermore, analysis was conducted to assess the effects of the two specific inversion methods on AOD values and AOD distribution characteristics in Beijing. The results indicate the following: 1) both the DT method and the VNIR method can be used successfully in the inversion of AOD in Beijing with Landsat 8 satellite data, while the DT method generates a slightly higher accuracy than that of the VNIR method, in which the root mean squared error (RMSE) values are 0.195 and 0.282, respectively; 2) AOD distribution in Beijing is presented with significant regional features, in which the areas with high AOD values were mainly concentrated in six districts (Dongcheng, Xicheng, Chaoyang, Fengtai, Haidian, and Shijingshan) and their surrounding areas. In addition, the AOD values are relatively low in the southwestern and northern regions of Beijing, which was mainly due to minor impacts of human activity and transportation.

1. Introduction

Atmospheric aerosols are a poly-disperse system suspended in the atmosphere, which are composed of solid and liquid microscopic particles and gas carriers. The particle sizes range from 10^{-3} μm–10^{2} μm (Whitby, 1978). Common aerosol particles include plant spores, pollen, microorganisms, smoke particles, dust, and fog droplets. As an essential component of the Earth-atmosphere system, aerosols have important impacts on the atmospheric environment and human health (Schwartz et al., 1995; Hansen et al., 1997; Suess and Prather, 1999). Aerosol optical depth (AOD) is defined as the integrated extinction coefficient over a vertical column of specific cross section, in which extinction coefficient is the fractional depletion of radiance per path length. Therefore, AOD can reflect the degree to which aerosols prevent the transmission of light (Hadjimitsis et al., 2012). Because AOD is a physical quantity that indicates the degree of solar radiation weakened by aerosols, it can indirectly reflect the aerosol concentration and degree of regional atmospheric pollution.

With increased environmental deterioration in recent years, it is urgent to enhance the monitoring and analysis of the atmospheric environment for emission reductions. Currently, many research methods have been developed to study aerosols based on satellite remote sensing, mainly including the multi-angle polarization method (Herman et al., 1997), DT method (Kaufman and Sendra, 1988), structure-function method (Tanré et al., 1988), deep blue method based on surface reflectance (Hsu et al., 2004), and the improved DT method (i.e., the DT method) (Levy et al., 2007). Reviews of aerosol retrieval using remote sensing images have been provided by many researchers. During the 1990s, Holben et al. (1992) introduced the structure-function method to invert AOD from the total atmospheric transmittance (Holben et al., 1992). Kaufman et al. (1997) discovered from large quantities of experimental data that linear correlations existed amongst the reflections of red, blue, and mid-IR bands in dense vegetation areas. On that

---

* Corresponding authors.
E-mail address: ouyangcnu@gmail.com (Y. Ou).
Peer review under responsibility of Turkish National Committee for Air Pollution Research and Control.

http://dx.doi.org/10.1016/j.apr.2016.09.004
1309-1042/Copyright © 2016 Turkish National Committee for Air Pollution Research and Control. Production and hosting by Elsevier B.V. All rights reserved.

Please cite this article in press as: Ou, Y., et al., Landsat 8-based inversion methods for aerosol optical depths in the Beijing area, Atmospheric Pollution Research (2016), http://dx.doi.org/10.1016/j.apr.2016.09.004

basis, they proposed the inversion method for the land AOD based on Moderate-Resolution Imaging Spectroradiometer (MODIS) remote-sensing images (i.e., the DDV method, Kaufman et al., 1997). Based on those results, Levy et al. (2010) made improvements and generated a more mature DT method (i.e., the DT method), which has been a classical method widely used in remote sensing applications for atmospheric aerosols and provided AOD products for global usage. As a technically mature satellite remote-sensing platform, MODIS has been widely utilized for the retrieval of AOD around Asia (Li et al., 2013; He et al., 2010; Che et al., 2015; Mehta et al., 2015) with aerosol products of 1 km, 3 km or 10 km spatial resolution, which is essential to the study of large regional aerosols. However, low spatial resolution limited its applications during the study of urban aerosols. Since then, numerous studies have been conducted. Hou et al. and Luo et al. successfully inversed Beijing's AOD using a modified dark-pixel method and Landsat 7 satellite images (Hou et al., 2012; Luo et al., 2015). The remote sensing of AOD in the Taklimakan Desert was analyzed using the ground—based sun—photometer. It was indicated from the results that the dust aerosol layer is higher in spring and summer (Zong et al., 2015).

The successful launch of Landsat 8 in February 2013 has allowed applications of satellite remote sensing to become further advanced. Landsat 8 can continuously collect the same types of data previously acquired by Landsat 5 and Landsat 7; however, it possesses more wave bands and finer wave band divisions (Table 1). Currently, Landsat 8 satellite images can be applied to the calibration and radiometric characterization of surface reflectance, surface albedo, surface temperature, evapotranspiration and drought, agriculture, land cover, condition, disturbance and change, fresh and coastal waters and snow and ice (Roy et al., 2014). Rajitha et al. (2015) identified the influence of cirrus clouds on NDVI and AFRI values and evaluated the potential of replacing NDVI with AFRI when cirrus clouds affected Landsat 8 images, which revealed the impact of offshore wind farms on suspended sediments (Vanhellemont et al., 2014). However, AOD inversions based on Landsat 8 satellite images are rarely reported in Beijing.

In this study, Landsat 8 image data were used to retrieve AOD of the Beijing area via the DT method and VNIR ACM in combination with the 6S radiation transfer model. The derived AOD values were validated by the AERONET AOD data and the MOD04 data were used to evaluate the performances of the two algorithms. Finally, the spatial distribution of AOD in Beijing was analyzed.

2. Data and methods

2.1. Overview of the research area

Beijing is located at 39.92° N, 116.46° E, which is at the northern edge of the North China Plain. It covers an area of 16,410.54 km^2, and its terrain is characterized as mountainous in the northwest and low-lying plains in the southeast (Fig 1). Beijing is warm and semi-humid with all the typical characteristics of a temperate-zone land climate. The four seasons consist of short springs and autumns and long winters and summers. The annual precipitation is approximately 640 mm, with over 70% of that total occurring during summer. Beijing's prevailing wind direction exhibits apparent seasonal variations. The winds observed during winter typically originate from the north and northwest, while the summer winds primarily originate from the south and southeast. As a large and fast-developing city, Beijing has a dense population and serious atmospheric pollution. The vast amount of atmospheric pollutants primarily originate from major pollution sources, such as dust from vehicles, construction sites, and roads and air discharges from catering industries and coal burning (Yang et al., 2015).

Table 1
Landsat 8 OLI parameters.

Band	Type	Wavelength (μm)	Resolution (m)
Band1	Blue band	0.433–0.453	30
Band2	Blue band	0.450–0.515	30
Band3	Green band	0.525–0.600	30
Band4	Red band	0.630–0.680	30
Band5	Near infrared	0.845–0.885	30
Band6	Infrared	1.560–1.660	30
Band7	Infrared	2.100–2.300	30

2.2. Principle for inverting the AOD

The scattering and absorption of incident radiation by aerosol particles may change the properties and strength of incident radiation, which can be measured to invert the properties of aerosol particles. That process forms the basis for the inversion of AODs in remote sensing.

Assuming that the ground surface is uniform (Lambertian) and that the vertical atmospheric variation is uniform, the apparent reflectance can be expressed using the following formula (Vermote et al., 1997a):

$$\rho_{TOA}(\theta_s,\theta_v) = \rho_0(\theta_s,\theta_v) + \frac{T(\theta_s)\cdot T(\theta_v)\cdot \rho_s(\theta_s,\theta_v)}{1 - S\cdot \rho_s(\theta_s,\theta_v)}, \tag{1}$$

where ρ_{TOA} is apparent reflectance; ρ_0 is radiation reflectance of an atmospheric layer; θ_s and θ_v are zenith angles of the Sun and satellite, respectively; $T(\theta_s)$ and $T(\theta_v)$ are transmittances for upward and downward radiation, respectively; S is the spherical albedo of the atmosphere; and ρ_s is surface reflectance.

Therefore, when the values for ρ_0, S, and $T(\theta_s)\cdot T(\theta_v)$ are known, the apparent reflectance can be calculated based on the surface reflectance; thus, Equation (1) can be transformed and expressed as:

$$\rho_s = \frac{(\rho_{TOA}(\theta_s,\theta_v) - \rho_0(\theta_s,\theta_v))/T(\theta_s)\cdot T(\theta_v)}{1 + S\cdot(\rho_{TOA}(\theta_s,\theta_v) - \rho_0(\theta_s,\theta_v))/T(\theta_s)\cdot T(\theta_v)}. \tag{2}$$

A comparison of Equation (2) with the atmospheric correction equation in the 6S radiation transfer mode (Vermote et al. 1997b), $\rho_s = x_a\cdot L - x_b/1 + x_c\cdot(x_a\cdot L - x_b)$, the following equation can be obtained:

$$\begin{cases} T(\theta_s)\cdot T(\theta_v) = \rho_{TOA}(\theta_s,\theta_v)/(x_a\cdot L) \\ \rho_0(\theta_s,\theta_v) = x_b\cdot \rho_{TOA}(\theta_s,\theta_v)/(x_a\cdot L) \,. \\ S = x_c \end{cases} \tag{3}$$

The values of x_a, x_b, and x_c that correspond to AOD can be determined from the Radiometric Lookup Table (LUT). For each target image pixel, ρ_0, S, and $T(\theta_s)\cdot T(\theta_v)$ can be calculated and used to obtain the apparent reflectance for different AOD values according to the surface reflectance values determined from Equations (1), (2), and (3). Finally, the calculated and real apparent reflectance was interpolated to derive the AOD in the red band (Xu, 2014).

2.3. Determination of dark pixels and surface reflectance

2.3.1. MODIS Dark Target (DT) Method to determine dark pixels and surface reflectance

Levy et al. (2010) integrated Kaufman's classic dark-pixel method and proposed an improved dark-pixel method (i.e., DT method), which considered the effects of vegetation index and

Please cite this article in press as: Ou, Y., et al., Landsat 8-based inversion methods for aerosol optical depths in the Beijing area, Atmospheric Pollution Research (2016), http://dx.doi.org/10.1016/j.apr.2016.09.004