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Determination of boundary layer top on the basis of the characteristics of atmospheric particles

Boming Liu[a], Yingying Ma[a,b,*], Wei Gong[a,b], Ming Zhang[a], Jian Yang[a]

[a] State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing (LIESMARS), Wuhan University, Wuhan, 430079, China
[b] International Research Center of Satellite Remote Sensing and Atmospheric Monitoring, Wuhan University, Wuhan, 430079, China

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ABSTRACT

The planetary boundary layer (PBL) is the lowest layer of the atmosphere that can be directly influenced with the Earth's surface. This layer can also respond to surface forcing. The determination of the PBL is significant to environmental and climate research. PBL can also serve as an input parameter for further data processing with atmospheric models. Traditional detection algorithms are susceptible to errors associated with the vertical distribution of aerosol concentrations. To overcome this limitation, a maximum difference search (MDS) algorithm was proposed to calculate the top of the boundary layer based on differences in particle characteristics. The top positions of the PBL from MDS algorithm under different convection states were compared with those from conventional methods. Experimental results demonstrated that the MDS method can determine the top of the boundary layer precisely. The proposed algorithm can also be used to calculate the top of the PBL accurately under weak convection conditions where the traditional methods cannot be applied. Finally, experimental data from June 2015 to December 2015 were analysed to verify the reliability of the MDS algorithm. The correlation coefficients R^2 (RMSE) between the results of MDS algorithm and radiosonde measurements were 0.53 (115 m), 0.79 (141 m) and 0.96 (43 m) under weak, moderate and strong convections, respectively. These findings indicated that the proposed method possessed a good feasibility and stability.

1. Introduction

The planetary boundary layer (PBL) is the lowest layer of the atmosphere that is directly influenced with the Earth's surface; this layer can also respond to surface forcing (Stull, 1988). The PBL exerts a remarkable effect on local and regional weather forecasts (Mao et al., 2009) and radiation transmission. Propagation of cloud nuclei and dispersion of pollutants are also driven by processes within the PBL (Emeis et al., 2008). Hence, the PBL is considerably significant to human wellbeing (Seibert et al., 2000); determining its height accurately is also important in understanding the dynamics that occur within it.

A Lidar system is an active remote sensing apparatus that provides backscatter information with high vertical and temporal resolution (Huang and Gong, 2011; Kovalev and Eichinger, 2004; Liu et al., 2015, 2018). These qualities make this system a powerful tool for investigating the optical properties and movement of the atmosphere's major particulate constituents. Ground-based and satellite Lidar systems can be used to characterise the vertical distribution of aerosols within the atmosphere (Davis et al., 2000; Mao et al., 2011; Li et al., 2017). According to this vertical aerosol profile, the height of the PBL (BLH) can be inferred (Matthias et al., 2004; Huang et al., 2010). To utilise the power of Lidar data in describing the PBL completely, stable and effective algorithms are needed to manipulate these large datasets. Many algorithms are currently used to determine the BLH; these algorithms include the gradient method (Hayden et al., 1997), wavelet covariance transform (WCT) method (Brooks, 2003), maximum variance technique (Jordan et al., 2010) and ideal profile fitting method (Steyn et al., 1999). The gradient method is largely affected with noise common to the complex backscatter of atmospheric layers. Although filtering or averaging the signal can reduce this problem (Mao et al., 2011), it can also distort the signal or decrease the temporal resolution of the Lidar data. The WCT method is appropriate for processing complex special cases because the operator can select an appropriate base function and set an appropriate threshold (Davis et al., 2000; Baars et al., 2008). The ideal profile fitting method developed by Steyn et al. is an effective method for delineating well-mixed boundary layers, but it is a less effective approach for complex aerosol layers (Mao et al., 2013; Hageli et al., 2000). These traditional algorithms identify the top of the boundary layer based on the vertical distribution of aerosol

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[*] Corresponding author. State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing (LIESMARS), Wuhan University, Wuhan, 430079, China.
E-mail address: yym863@whu.edu.cn (Y. Ma).

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concentration. However, when the vertical distribution of aerosols becomes non-uniform or affected with multilayer aerosols, the accurate determination of the top of the boundary layer using these Lidar algorithms is difficult (Tang et al., 2016; Wang et al., 2012). To overcome these limitations, this paper proposes a maximum difference search (MDS) algorithm based on the differences in particle characteristics to determine the top of the boundary layer. We use differences in particle size and extinction ability, instead of evaluating the vertical distribution of aerosol concentration, to determine the top of the boundary layer.

In the present study, we utilised a two-wavelength polarisation Lidar system to determine the top of the boundary layer. Firstly, a detailed description of the MDS method was provided to obtain the BLH from the Lidar system. Secondly, the result of the boundary layer was obtained by utilising the proposed and traditional algorithms under different convection states. Finally, the BLH from Lidar data during June 2015 to December 2015 was compared with the radiosonde (RS) measurements to verify the reliability of the MDS method.

2. Study sites and instrumentation

The ground-based Lidar system used in this study is located at Wuhan University (114°21′E, 30°32′N), Guangbutun, China at the Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing. The instrument is positioned at 39 m above sea level and surrounded with buildings (Wei et al., 2015). This two-wavelength polarisation Lidar system consists of a laser transmitter system, receiving telescope and data acquisition and processing subsystems. The Lidar transmitter functions at 532 and 355 nm with the aid of a Nd:YAG pulse laser. The signals are detected by the photomultiplier tubes and fed into an amplifier. The amplifier outputs are connected to a PC-based data acquisition system. The system provides a backscatter signal with a temporal resolution of 1 s and a vertical spatial resolution of 7.5 m. Further details about this system are provided in a previous study (Liu et al., 2017).

3. Principles and methods

In terms of its vertical structure, the atmospheric boundary layer includes the near-surface layer, mixed layer and entrainment layer (Stull, 1988). During daytime, atmospheric activity intensifies, and the entrainment layer is incorporated into the mixed layer. Nevertheless, the entrainment layer may appear under weak convection conditions (Seibert et al., 2000). Therefore, in this paper, the top of the entrainment layer is regarded as the top of the boundary layer. Aerosol particles are abundant within the boundary layer. A free atmosphere exists with mostly atmospheric molecules and few aerosol particles above the boundary layer, as shown in Fig. 1(a) and (b). According to previous research (Sugimoto et al., 2002), the properties of atmospheric particles at different heights also differ. Fig. 1(c) shows a scatter plot of the colour ratios (CR) and backscatter coefficients (BC) on 7 December 2015. Different heights are indicated with different colours. Different particles are distributed in different areas. Most of the particles of the upper atmosphere (above the boundary layer) are gas molecules and concentrated in the red rectangular area with a low CR and small BC. Nonetheless, atmospheric particles near the ground (below 1 000 m) are mainly aerosol particles and concentrated in the black rectangular area with a high CR and large BC. Fig. 1(d) illustrates the profile of CR and BC scatter plot for 03:00 (LT) on 8 December 2015. Aerosol particles are concentrated in the black elliptical area, and molecular particles are concentrated in the red circular area. These findings suggested that the top of the boundary layer is located between these two areas. Therefore, we aimed to determine the top of the boundary layer based on the different characteristics of particle wavelength ratios and BC.

The vertical resolution of the Lidar signal is 7.5 m, and each sample point represents the characteristics of atmospheric particles at the corresponding height. Results indicated differences in the characteristics of particles between different heights, such as differences in particle size (represented by different CR) and particle extinction (represented by different BC). Simultaneously, the atmospheric molecules are above the boundary layer, and the aerosol particles are within the boundary layer. The sizes and extinction capacities of aerosol particles are much larger than those of atmospheric molecules. Therefore, the differences should be the largest between a sampling point on the boundary layer and another above the boundary layer. On the basis of this principle, we proposed a MDS algorithm to calculate the top of the boundary layer.

3.1. Establishing the eigenvalues

The Lidar signal P(r) can be expressed with the Lidar equation, which can be written as follows (Fernald et al., 1972; Fernald, 1984):

$$P(r) = CP_0 r^{-2}\left[\beta m(r) + \beta a(r)\right]\exp\left[-2\int_0^r [\alpha m(r) + \alpha a(r)]dr\right] + P_{nb} \tag{1}$$

where r is the range; C is Lidar constant; P_0 represents the emitted energy; $\beta_m(r)$ and $\beta_a(r)$ are the molecule and particle BC, respectively; $\alpha_m(r)$ and $\alpha_a(r)$ are the molecule and particle extinction coefficients, respectively; and noise P_{nb} is considered Gaussian. On the basis of the Lidar equation, we can obtain the echo signal of each channel. These echo signals were used to calculate the BC and CR. The BC and CR are expressed as follows (Liu et al., 2017):

$$\begin{cases} BC = \beta_{532} \\ CR = k\frac{\beta_{532}}{\beta_{355}} \end{cases} \tag{2}$$

where β_{355} and β_{532} represent the 355 and 532 channel BC, respectively, and k is the ratio of the channel constant, which is dependent on the instrument used. The BC indicates the extinction intensity of particles at 532 nm. The large BC value results in strong extinction ability of the particles. The CR represents the wavelength ratio of the 532 and 355 nm wavelengths. The value indicates the size of the particles; a large CR suggests large particles. Therefore, we selected the BC and the CR signal to construct the eigenvalues. The eigenvalue A represents the difference in size between adjacent particles calculated from the CR of adjacent particles. The eigenvalue B represents the difference in extinction capability between adjacent particles calculated from the BC of adjacent particles. These values can be expressed as follows:

$$\begin{cases} A(i) = CR(i) - CR(i-1) \\ B(i) = BC(i) - BC(i-1) \end{cases} \tag{3}$$

where CR(i) represents the CR of the sample point i, A(i) represents the difference of particle size between the sample points i and $i-1$, BC(i) represents the BC value of the sample point i, and B(i) represents the difference in the particle extinction ability between the sample points i and $i-1$. To facilitate the interpretation of eigenvalues, we provided a case analysis for 3:00 LT on 8 December 2015 in Wuhan. Fig. 2(a) and (b) show the sequences of eigenvalues A and B, respectively. Notably, the near-ground signal with overlap is processed. The sequences of eigenvalues A and B show many peaks. In this study, the eigenvalue sequence peaks were regarded as the top or base of the aerosol layer. The blue circle represents the point where the weak aerosol layer turns into a strong aerosol layer, which typically indicates the base of the aerosol layer. The orange circle represents the point where the strong aerosol layer turns into a weak aerosol layer, which typically indicates the top of the aerosol layer.