Research Progress on Estimation of the Atmospheric Boundary Layer Height

Hongsheng ZHANG¹, Xiaoye ZHANG²*, Qianhui LI¹, Xuhui CAI³, Shaojia FAN⁴, Yu SONG³, Fei HU⁵, Huizheng CHE², Jiannong QUAN⁶, Ling KANG³, and Tong ZHU³

¹ Laboratory for Climate and Ocean–Atmosphere Studies, Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing 100871
² State Key Laboratory of Severe Weather and Key Laboratory of Atmospheric Chemistry of CMA, Chinese Academy of Meteorological Sciences, China Meteorological Administration (CMA), Beijing 100081
³ State Key Joint Laboratory of Environmental Simulation and Pollution Control, Department of Environmental Science, Peking University, Beijing 100871
⁴ School of Atmospheric Sciences, Sun Yat-sen University, Guangzhou 510275
⁵ State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029
⁶ Institute of Urban Meteorology, China Meteorological Administration, Beijing 100081

(Received December 10, 2019; in final form March 24, 2020)

ABSTRACT

Atmospheric boundary layer height (ABLH) is an important parameter used to depict characteristics of the planetary boundary layer (PBL) in the lower troposphere. The ABLH is strongly associated with the vertical distributions of heat, mass, and energy in the PBL, and it is a key quantity in numerical simulation of the PBL and plays an essential role in atmospheric environmental assessment. In this paper, various definitions and methods for deriving and estimating the ABLH are summarized, from the perspectives of turbulent motion, PBL dynamics and thermodynamics, and distributions of various substances in the PBL. Different methods for determining the ABLH by means of direct observation and remote sensing retrieval are reviewed, and comparisons of the advantages and disadvantages of these methods are presented. The paper also summarizes the ABLH parameterization schemes, discusses current problems in the estimation of ABLH, and finally points out the directions for possible future breakthroughs in the ABLH-related research and application.

Key words: atmospheric boundary layer height (ABLH), turbulent boundary layer, aerosol accumulation layer, remote sensing retrieval, parameterization

Citation: Zhang, H. S., X. Y. Zhang, Q. H. Li, et al., 2020: Research progress on estimation of the atmospheric boundary layer height. J. Meteor. Res., 34(3), 482–498, doi: 10.1007/s13351-020-9910-3.

1. Introduction

Land–atmosphere interactions change the nature of the lower troposphere and extend the influence of the surface to a few hundred up to a few thousand meters above the surface, which is the atmospheric boundary layer (ABL). As the lowest layer of the troposphere, the ABL is directly affected by surface forcing, with response time to surface forcing less than one hour (Stull, 1988). When the interaction between the atmosphere and a specific underlying surface, such as the biomass or the ocean, is emphasized, the ABL can be referred to as an ecological boundary layer (Wang and Xiong, 1993) or an air–sea boundary layer (Gao, 1994). Because of the existence of various surface forcing processes, such as friction drag, evaporation, transpiration, and heat transfer, turbulence is the main form of motion in the ABL. From the perspective of turbulence, the ABL is the lower atmosphere with motions at various scales, in which turbulent transport plays an important role and obvious diurnal variations of
meteorological elements are observed (Sheng et al., 2013). Turbulent transport makes the ABL not only a bridge and channel for the exchange of heat, moisture, energy, and substance between the ground and the air, but also an important place for the interaction of multiple layers such as the atmosphere, lithosphere, and biosphere. The ABL also plays a key role in occurrences of weather events, climate change, hydrothermal circulation, and so on (Liu H. Z. et al., 2018; Yang, 2018).

The atmospheric boundary layer height (ABLH) is an important parameter to characterize the ABL and an important physical variable in numerical simulations of the atmosphere and in environmental assessment (Zhang et al., 2011). It reflects a combined effect of turbulent mixing, convection, and other physical processes in the boundary layer, and in turn affects the vertical distributions of mass and energy, such as heat, water vapor, and aerosols. In weather forecasting and air quality forecasting models, the ABLH is used to determine vertical diffusion as well as the deposition and transport of pollutants (Seibert et al., 2000; Dai et al., 2014).

In recent years, severe air pollution events have occurred in China frequently, and the relationship between the ABL and pollution has aroused widespread attention (Zhong et al., 2018; Ren et al., 2019a, b; Zhang et al., 2019; Quan et al., 2020; Wei et al., 2020). According to the study on the spatial distribution of ABLH in China (Zhao et al., 2019), the ABLH tended to decrease in most areas where the air quality declined. ABLH is the main meteorological parameter leading to the interdecadal variation in PM$_{2.5}$ concentration in North China, Northeast China, and the Sichuan basin (Gui et al., 2019). There is a negative correlation between ABLH and the concentration of pollutants near the surface, which can be expressed by a power function under the convective condition (Du et al., 2013; Quan et al., 2013; Li et al., 2020a). Heavy pollution is often associated with low ABLH, which is usually no more than 1000 m (Qu et al., 2017). An increase in aerosol content can weaken solar radiation reaching the surface, strengthen the temperature inversion, and weaken the turbulent diffusion in the ABL through the aerosol–boundary layer feedback, resulting in the decrease of ABLH, while water vapor and pollutants further accumulate (Ding et al., 2013; Li Z. Q. et al., 2017; Zhong et al., 2017; Zou et al., 2017).

According to its thermodynamic properties and turbulence characteristics, the ABL can be categorized into three types: unstable, neutral, and stable. Surface heating makes an unstable stratification of the atmosphere above the ground, forming the unstable boundary layer, where the turbulence is extremely active due to the work done by buoyancy. Thermal bubbles are the basic form of turbulence in the unstable boundary layer, which make the vertical distribution of meteorological elements nearly uniform. Therefore, the ABL is also called convective boundary layer or mixed layer. When the lower atmosphere maintains neutral stratification, it is called the neutral boundary layer, where the work done by buoyancy can be ignored. The stable boundary layer with an inversion layer is formed by radiative cooling of the surface at night. In general, the height of the convective boundary layer is below 2000–3000 m, and the height of the stable boundary layer is no more than 500 m (Garratt, 1994; Liu and Liang, 2010). But in arid and monsoon climate zones, the height of the boundary layer can be up to 4000–5000 m (Raman et al., 1990; Marsham et al., 2008; Zhang and Wang, 2008; Han et al., 2015; Zhao et al., 2018). Geographic location, weather and climate conditions, and differences in the underlying surface all increase the complexity of research on the height of the boundary layer (Ma et al., 2011; Li et al., 2020b).

The ABLH cannot be obtained by conventional surface observations; it is diagnosed from vertical profiles of meteorological elements such as temperature, humidity, and wind speed. Traditional observations directly obtain vertical profiles of meteorological elements by radiosondes, tethered balloons, meteorological towers, and aircraft, avoiding the retrieval errors, so the accuracy and reliability of the data are relatively high. With the development of remote sensing, ground-based remote sensing techniques such as lidar, microwave radiometer, ceilometer, sodar, wind profiler, and Radio Acoustic Sounding System (RASS), have played important roles in boundary layer detection. These techniques help achieve continuous observations of the ABL and collect data at a high temporal resolution. Furthermore, to solve the problem of poor representativeness of single-station observation, some studies adopted satellite remote sensing that has a wider coverage to retrieve the height and distribution of the global ABL by using the Global Positioning System (GPS) radio occultation technique (Ratnam and Basha, 2010; Ao et al., 2012).

The ABLH-related research and application have developed significantly in the past several decades, but no comprehensive and in-depth review is carried out on this specific topic. To fill this gap, the present paper reviews various definitions of the ABLH, introduces different methods for deriving and estimating the ABLH by traditional detection and remote sensing approaches, and compares the advantages and disadvantages of different methods. Parameterization schemes for the ABLH are also summarized, and the existing problems are dis-
cussed. Finally, future perspectives for reasonable and effective estimation of the ABLH are presented.

2. Deriving/estimating the ABLH

The ABLH can be derived/estimated from four approaches, namely, the turbulent motion approach, the thermodynamic effect approach, the dynamic effect approach, and the substance distribution approach.

2.1 The turbulent motion approach

From the perspective of turbulent motion, ABLH is the thickness of the lowest layer of the troposphere where turbulence persists. The height at which the turbulent energy or stress almost disappears can be regarded as the top of the ABLH (Zhao et al., 1991; Dai et al., 2014). The height of the convective boundary layer can be considered as the height at which the sign of the turbulent heat flux changes, the turbulent heat flux exhibits a negative maximum value, or the dissipation rate of turbulent kinetic energy (TKE) and vertical velocity variance significantly decrease. The height of the stable boundary layer can be regarded as the height at which the values of relevant turbulence parameters are reduced to a few percent of those of the surface layer (Beyrich, 1997; Kosović and Curry, 2000; Vickers and Mahrt, 2004). These parameters include vertical heat fluxes, momentum fluxes, vertical velocity variance, TKE, and so on. In addition, based on the theory that the maximum turbulent eddy size of the convective boundary layer is related to the boundary layer height, some studies calculated the height of the convective boundary layer from the wind velocity spectra using surface turbulence observation (Liu and Ohtaki, 1997; Song et al., 2006; Saraiva and Krusche, 2013). This turbulence-based approach has solid theoretical foundation; however, it is difficult to observe the vertical distribution of turbulence. In practical applications, the turbulent motion is often reflected in the thermodynamic effect, dynamic effect, and vertical distribution of substance.

2.2 The thermodynamic effect approach

Considering the thermodynamic effect, the ABLH refers to the height at which the temperature gradient is obviously discontinuous, or the diurnal temperature variation nearly disappears (Zhao et al., 1991). In the daytime, the height of the mixed layer or the position of the capping inversion layer is usually regarded as the top of the convective boundary layer; while at night, the height of the surface-reaching inversion layer is defined as the height of the stable boundary layer (Yamada, 1976). Obtaining the ABLH based on thermodynamic effects has a certain theoretical basis in turbulence theory, and it is easily achieved and has been widely used. However, considering thermodynamic effects alone has its limitations, as the formation of the ABL combines both dynamic and thermodynamic mechanisms. Commonly used methods for determining the ABLH based on thermodynamic effects include potential temperature gradient method (Liu and Liang, 2010) and the Holzworth method (i.e., the dry adiabatic method or the “parcel method;” Holzworth, 1964). The latter can only be used for unstable conditions, and it cannot describe the diurnal variation of the ABL (Emeis and Türk, 2004).

2.3 The dynamic effect approach

Dynamically, the ABLH is defined as the height at which the wind approaches the geostrophic wind, or the height at which there appears a wind maximum (Zhao et al., 1991). A prerequisite for determining the ABLH using the first definition is that the atmosphere is horizontally homogeneous and barotropic; however, it is difficult to satisfy this hypothesis in reality. As the stable boundary layer obstructs the downward momentum transfer at night, a wind maximum is usually generated at the top of the layer; thus, the height of the wind maximum is often regarded as the height of the stable boundary layer in practice (Mahrt et al., 1979). However, some studies have shown that the height of the wind maximum may not increase with time as it should be (Hyun et al., 2005). In this regard, Hyun et al. (2005) proposed a method to estimate the height of the stable boundary layer based on the wind shear ($S$). In their study, the height of the stable boundary layer was defined as the height at which the wind shear was less than the threshold $S_c$ for the first time, or less than $S_c$ for the first time above the local wind maximum. If the maximum wind shear is lower than the threshold, its corresponding height is taken as the height of the stable boundary layer. Dai et al. (2014) provided an optimal range of the threshold.

2.4 The substance distribution approach

Regarding the distribution of substance, the ABLH can be determined based on the spatial distribution of tracers, such as water vapor and aerosol. The water vapor or aerosol is abundant in the ABL, while its content decreases rapidly in the free atmosphere (Stull, 1988; Emeis and Schäfer, 2006; Shi et al., 2019a). Therefore, the height at which the gradient of humidity or aerosol concentration is obviously discontinuous can be taken as the ABLH. In the 1960s and 1970s, early attempts confirmed the feasibility of depicting atmospheric motions
and diurnal variation of the ABL structure based on the distribution of substance (Collis and Ligda, 1964; Collis et al., 1964; Utue, 1972; Russell et al., 1974). Shi et al. (2020) referred to the height determined by the distribution of substance as “material boundary layer height,” indicating the maximum depth of the vertical diffusion of substance. The concept of “boundary layer” in atmospheric science is derived from turbulent motion, which includes the spatial and temporal variations of meteorological elements, and the characteristics of turbulent flows. However, the “material boundary layer” is different from the traditionally defined boundary layer, for the distribution characteristics of aerosol, as well as water vapor and CO$_2$, differ from those of meteorological elements. To avoid confusion, we use “aerosol accumulation layer” to highlight the characteristics of the distribution of aerosol in the lower atmosphere.

In general, the aerosol accumulation layer corresponds to the convective boundary layer in the daytime, and the height at which the specific humidity or aerosol concentration decreases rapidly is regarded as the top of the convective boundary layer. The turbulent transport at night is weak, so the height of the near-surface layer with high specific humidity or high aerosol concentration is taken as the top of the stable boundary layer. Differences of the aerosol concentration between ABL and free atmosphere can be clearly observed from echo signals. Therefore, the aerosol accumulation layer provides a basis for remote sensing methods to determine the ABLH (Bravo-Aranda et al., 2017; Shi et al., 2019b).

### 3. Retrieval of the ABLH by remote sensing

#### 3.1 Ground-based remote sensing

3.1.1 Aerosol lidar and ceilometer

Aerosol lidars and ceilometers are the most widely used ground-based remote sensing devices for observing the boundary layer in recent years. These two devices retrieve the ABLH with the same principle, i.e., aerosols and other substances are used as tracers to correlate the strength of the backscatter signals with the content and distribution of aerosols in the atmosphere (Emeis et al., 2008; Tsaknakis et al., 2011; Yin et al., 2019). Assuming that there are no other sources and sinks, aerosols and other substances are emitted from the ground into the ABL. After sufficient time, they are uniformly mixed in the boundary layer by turbulent diffusion, forming an aerosol accumulation layer. The capping inversion layer with stable stratification at the top of the boundary layer inhibits the transport of aerosols to the free atmosphere, making the air cleaner in the free atmosphere (He et al., 2006; Pearson et al., 2010; Haeffelin et al., 2012). The transmission of optical signals in the atmosphere is affected by water vapor and aerosols; therefore, lidar backscatter signals are attenuated rapidly at the boundary layer top with large gradients. Based on this, the ABLH can be estimated (Eresmam et al., 2006; Shen et al., 2017). Lidar signals can be significantly attenuated in heavy fog, rain, and snow, so the measurement accuracy may be significantly affected; consequently, lidar has limited applications in complex weather conditions (Caicedo et al., 2017). Compared with lidars, ceilometers use the near-infrared band, which is safe to eyes. In addition, it is easy to maintain and is low in cost (Kothaus and Grimmond, 2018; Yin et al., 2019).

The following six methods are commonly used to extract the ABLH from backscatter signals, and can also be used in combination (Sawyer and Li, 2013; Poltera et al., 2017).

1. The threshold strategy. The ABLH is defined as the height at which the backscatter signal is below the threshold, which is the critical intensity of the backscatter signal. The threshold strategy requires systematic data correction and averaging, and it has high indeterminacy if the signal-to-noise ratio (SNR) is low (Melfi et al., 1985; Menut et al., 1999; Münkel and Räsänen, 2004).

2. The gradient method. After calculating the gradient of the backscatter signal, the height at which the minimum value of the first derivative of the backscatter signal occurs is considered as the mixed layer height (Flamant et al., 1997; Hennemuth and Lammert, 2006). Some studies used the minimum value of the second derivative or the minimum value of the first derivative of the logarithmic function to determine the ABLH (White et al., 1999; Sicard et al., 2004). To eliminate the influence of the non-uniform spatial distribution of aerosols on lidar signals, He et al. (2006) proposed to calculate the gradient of the standardized backscatter signal. Yang et al. (2017) considered the influence of gravitational waves on the atmospheric structure and defined the ABLH as the height at which the minimum of cube root gradient of backscatter signal occurs, which has improved the accuracy of determination (Fan et al., 2019). The gradient method can be easily applied but has poor stability. Its results can be significantly affected by the local structure of the signal profile, so it has high requirements for the quality of data (He et al., 2006; Wang L. et al., 2012; Li et al., 2018).

3. The standard deviation method. Standard deviation reflects the degree of dispersion of the backscatter signal at a certain height. The larger the value, the stronger the dispersion, and more drastic the variation.
Given the strong entrainment at the top of the mixed layer, dramatic variation of the backscatter signal occurs at the top of the boundary layer. As a consequence, the height at which the maximum standard deviation of the signal occurs can be regarded as the ABLH (Hooper and Eloranta, 1986; Yang et al., 2016).

(4) The wavelet covariance transform (WCT) method. The WCT method is used to detect sudden changes in the signal. The larger the value of the WCT function, the higher the similarity between the signal and wavelet function, and the greater the signal variation. Therefore, the height at which the WCT function obtains the maximum value is the ABLH (Davis et al., 2000; Deng et al., 2014).

(5) The curve fitting method. It is assumed that the ideal backscatter profile satisfies the simplest characteristics of the mixed layer; that is, the backscatter signal intensity in the mixed layer is strong and almost constant, but it declines rapidly at the top of the mixed layer. An ideal profile is fitted based on the observed backscatter profile. The height corresponding to the minimum root-mean-square error (RMSE) of the ideal curve and the measured profile is regarded as the ABLH (Steyn et al., 1999; Eresmaa et al., 2006; Peng et al., 2017).

The gradient method, the standard deviation method, and the WCT method show similar results in ABLH estimation, and are quite sensitive to noise (Haefelin et al., 2012; Yin et al., 2019). The curve fitting method is less affected by the local structure of the profile, and it still has high stability with a low SNR. However, its computational cost is relatively high (Steyn et al., 1999; Li H. et al., 2017).

(6) The image edge detection method. The gradient of the backscatter signal has the greatest variation at the top of the boundary layer, corresponding to the edge of image of the backscatter signal (Xiang et al., 2016). A grayscale image is first drawn based on the backscatter signal. Then, filter out the image noise but retain the contour information. Next, a dual threshold operation is performed. Finally, the ABLH can be extracted through edge detection. Lewis et al. (2013) combined wavelet analysis with image edge detection to determine the optimal boundary layer height using fuzzy logic based on factors including time, value of the WCT function, and the height of the adjacent boundary layer. Their algorithm has high accuracy and is not easily affected by clouds or the residual layer.

Lidar (or ceilometer) has high temporal and spatial resolutions, and it can essentially detect the distribution of aerosols, i.e., the aerosol accumulation layer, which cannot fully represent the ABL defined from the perspective of turbulence. For example, the decrease in the height of the thermal boundary layer at night does not affect the aerosol distribution at high altitudes. The accumulation of aerosol in the residual layer can lead to an overestimation of the ABLH (Wang Z. et al., 2012; Bravo-Aranda et al., 2017; Caicedo et al., 2017). On account of complicated atmospheric motions, the vertical distribution of aerosols is often non-uniform and shows a multi-layer structure. Although the gradient method, the WCT method, and other methods may identify multiple heights, there are still many uncertainties in the selection of the optimal height (de Arruda Moreira et al., 2018; Su et al., 2020). In addition, the existence of clouds also increases the difficulty in determining the ABLH (Cohn and Angevine, 2000; Pearson et al., 2010; Liu B. M. et al., 2018).

Many studies have proposed new methods to determine the ABLH more accurately under complex conditions. Haefelin et al. (2012) suggested using information about radiation and surface temperature to obtain sensible heat fluxes to support the estimation of ABLH. Su et al. (2020) proposed the Different Thermo-Dynamical Stabilities (DTDS) algorithm considering the thermodynamic stability of the boundary layer with time, which helps to correct errors caused by the residual layer. Lange et al. (2014) tracked the ABL development by extended Kalman filter method, and simulated the ABL top with the profile of the shape of the error function. The filter can fit the shape function with the observed data self-adaptively and minimize the RMSE statistically, so the ABLH can be determined under low SNR conditions. To solve the interference of the residual layer, Saeed et al. (2016) proposed a method combining lidar and microwave radiometer observations, using an extended Kalman filter method to assimilate the observations from the two instruments, and the estimated height of the stable boundary layer was more accurate. Bravo-Aranda et al. (2017) proposed an algorithm, in which the WCT was applied to the range-corrected signal and the perpendicular-to-parallel signal ratio, and the ABLH was estimated based on lidar depolarization information. Liu B. M. et al., (2018) employed a dual-wavelength polarization lidar to obtain the aerosol color ratio and backscattering coefficients, which were used to establish the degree of difference. Considering the differences in characteristics of particles, they proposed a maximum difference search (MDS) algorithm, which can accurately determine the boundary layer top even under weak convection conditions.
3.1.2 Microwave radiometer

A microwave radiometer can obtain the atmospheric brightness temperature based on the microwave signals emitted and scattered in the atmosphere. Based on radiative transfer model and atmospheric background information, it determines the ABLH by retrieving the vertical distributions of temperature, relative humidity, and water vapor using Newton’s iteration, neural networks, and/or other techniques (Hewison, 2006; Liu, 2011).

Microwave radiometer can provide continuous observations with high temporal resolution, and it is easy to maintain. Compared to visible and near-infrared band, microwave band has good penetrability to the cloud, making it less disturbed by the cloud. Consequently, the microwave radiometer can provide information about temperature and humidity structure under different weather conditions (Kim and Lee, 2015). However, its vertical resolution is high at low altitudes, but relatively low at high altitudes; and there is a blind area issue that needs to be addressed. Water vapor profiles retrieved from the microwave radiometer can only reflect the average variation trend, but cannot present the subtle changes in water vapor (Yang et al., 2016). The accuracy of retrieval decreases significantly under precipitation conditions (Xu et al., 2014). Moreover, the accuracy of retrieval is relatively high in the lower atmosphere, but the retrieval error increases with altitude, and hence the retrieval techniques need further improvement (Liu and Zhang, 2010; Liu, 2011; Friedrich et al., 2012; Xu et al., 2015).

3.1.3 Sodar

Due to the non-uniform distribution of temperature in the atmosphere, the scattering intensity of acoustic signals is varied (Emeis et al., 2008). At the top of the convective boundary layer, the large temperature gradient and wind shear increase the turbulence and temperature fluctuations in the entrainment zone, resulting in the second largest values of both the temperature structure coefficient \(C^2_T\) and the backscatter intensity (Beyrich, 1995). In the stable boundary layer, the temperature structure coefficient has only a slight variation, in contrast to its significant decline observed at the top of the boundary layer; this helps estimate of the height of the stable boundary layer. Emeis and Türk (2004) introduced vertical velocity variance as a limiting condition based on the method proposed by Beyrich (1997) to help determine the boundary layer top.

Sodar can be easily applied and is less costly. Compared to other ground-based remote sensing instruments, it has a smaller blind area and a higher vertical resolution (Emeis and Türk, 2004; Kallistratova et al., 2018).

Despite its advantages, it has a limited detection range, which is often below 1000 m (Angevine et al., 1994; Beyrich, 1995). A mini-sodar has higher spatial and temporal resolutions, and the blind area is as low as 10 m (Seibert et al., 2000). Sodar is sensitive to environmental noise and causes noise pollution, so it has difficulty in application in cities. At present, sodar is rarely used to determine the ABLH, but often used to study the low-level jets and internal gravity waves in the stable boundary layer (Emeis et al., 2008; Kallistratova et al., 2018).

3.1.4 Wind profiler

A wind profiler can retrieve the horizontal wind, vertical velocity, and refractive index structure constants by the scattering signal of electromagnetic waves from clear air turbulence (Hu and Li, 2010). The echo signal received by the wind profiler mainly comes from the inhomogeneity of the radio refractive index, which can be characterized by the refractive index structure parameter \(C^2_n\). This parameter is mainly affected by temperature and humidity, and the influence of humidity is more obvious (Cohn and Angevine, 2000; Emeis et al., 2008; Collaud Coen et al., 2014). Studies have shown that the peak value of \(C^2_n\) occurred at the top of the convective boundary layer, and the SNR was proportional to \(C^2_n\) in a certain range (Fairall, 1991); therefore, the peak height of SNR can be used to estimate the top of the convective boundary layer (Angevine et al., 1994; Ge, 2017).

The boundary-layer wind profiler has good mobility. Its temporal and spatial resolutions can be less than 10 min and 50 m, respectively. It can provide information such as the thickness of the convective boundary layer and the entrainment zone. However, it is difficult to capture the lower boundary layer because of the large blind areas (Angevine et al., 1994); and the scattering echo signal of electromagnetic waves from clear air turbulence is usually weak, resulting in low SNR. Poor weather conditions such as rain and snow and the existence of cumulus clouds can all interfere with the echo signal (Hu and Li, 2010; Collaud Coen et al., 2014). Humidity has a significant influence on signals, but the moisture cannot mix as well as temperature, which may cause discrepancy in the ABLH determination (Seibert et al., 2000). As a combination of wind profiler and sodar, RASS can comprehensively obtain the vertical distributions of virtual temperature, wind, and \(C^2_n\), thereby improving the accuracy of ABLH determination.

3.1.5 Doppler wind lidar

The movement, relative to the lidar, of air molecules or particles in the atmosphere results in Doppler shift. The wind field can be retrieved by the Doppler shift
between the transmitted and backscatter signals (Chanin et al., 1989; Khaykin et al., 2016). Wind velocity variance can be used as a proxy variable to represent the characteristics of turbulent flow; thus, the ABLH can be retrieved based on the vertical velocity variance \( \sigma_w^2 \) obtained by the Doppler wind lidar (Banta et al., 2006; Schween et al., 2014; Shukla et al., 2014). In addition, some studies determined the ABLH using low-level jets and the turbulent energy dissipation rate retrieved by the Doppler wind lidar (de Arruda Moreira et al., 2015; O’Connor et al., 2010).

The height of the convective boundary layer can be determined by a threshold strategy. The critical value of \( \sigma_w^2 \) varies for different underlying surfaces (Tucker et al., 2009; Pearson et al., 2010; Barlow et al., 2011; Huang et al., 2017). Schween et al. (2014) found that a 25% variance in the threshold will cause a 7% deviation in the ABLH, so it is vital to select a suitable threshold according to the underlying surface. The turbulence in the stable boundary layer is weak, increasing uncertainties of the threshold \( \sigma_w^2 \). Therefore, the proportional method is commonly used to address this issue. Specifically, the height at which the \( \sigma_w^2 \) is reduced to a few percent (generally 0.05 or 0.1) of the maximum value near the ground is taken as the top of the stable boundary layer (Vickers and Mahrt, 2004; LeMone et al., 2014).

The Doppler wind lidar has high temporal and spatial resolutions, and wide range of detection. It can continuously sample the boundary layer and obtains information about atmospheric turbulence. It is more accurate to determine the ABLH with \( \sigma_w^2 \) than mean wind (Huang et al., 2017).

3.2 Satellite remote sensing

For satellite remote sensing, the ABLH can be retrieved by GPS radio occultation (RO) technique. The signals of GPS satellites are refracted through the earth’s non-uniform atmosphere, and the deviated signals are received by Low-Earth-Orbit (LEO) satellites. After a series of processing of the original signals, the sequence of bending angle and refractivity profile can be obtained. The bending angle and the refractivity decrease sharply at the boundary layer top, which can help determine the ABLH (Ratnam and Basha, 2010; Seidel et al., 2010; Ao et al., 2012). According to the relationship between the refractivity and the atmospheric thermodynamic properties, the vertical distribution of temperature and humidity can be further retrieved to determine the ABLH (Khaykin et al., 1996).

GPS signals are in microwave band, which are not affected by clouds and precipitation. In addition, the RO technique offers all-weather observations with a wide spatial coverage, which supplements the lack of observations over the ocean and extreme climate zones. These observations can help verify and improve relevant models and increase the accuracy of weather and climate forecasting (Kursinski et al., 1996). However, the minimum height of occultation observations may not reach the surface, and its retrieval accuracy in the lower atmosphere remains to be improved. Profiles retrieved by satellite remote sensing have coarse horizontal and vertical resolutions, which increase the uncertainty in the retrieval of heterogeneous underlying surfaces (Ao et al., 2012).

In summary, traditional observational methods and remote sensing techniques are essential to the determination of the ABLH in the observational domain, each of which has its own advantages and can complement each other. Table 1 supplements and summarizes the advantages and disadvantages of different observational methods based on the study of Seibert et al. (2000).

4. Forecast equations and diagnostic formulae for the ABLH

The ABLH can also be obtained through parameterization, i.e., calculating the ABLH through forecast equations and diagnostic formulae. Parameterization requires only a small amount of data and is easy to achieve. The application of this method has significance in places that lack sufficient observations. The following section introduces the forecast equations and diagnostic formulae for the ABLH.

4.1 Diagnostic formulae

There are usually two types of diagnostic formulae to calculate the equilibrium height of the stable boundary layer. The first type is based on surface fluxes, which requires information related to surface heat and momentum fluxes; the other type is based on the Richardson number, which uses information on atmospheric stratification and wind shear (Vickers and Mahrt, 2004).

4.1.1 Diagnostic formulae based on surface fluxes

Many studies have proposed a variety of formulae considering different factors influencing the stable boundary layer height, such as friction, earth’s rotation, surface fluxes, and background stratification (Zilitinkevich et al., 2007). Table 2 summarizes some diagnostic formulae based on surface fluxes. Because of the complex physical processes influencing the stable boundary layer, such as radiative cooling, gravity waves, night-
Table 1. Comparison of different observational methods for determining the ABLH

| Instrument                  | Advantages                                                                 | Disadvantages                                                                 |
|-----------------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| Direct observation          | Radiosonde: Direct observation of meteorological elements such as wind speed, temperature, and humidity to avoid retrieval errors; conventional observation and continuous data can be used for research on climate scale; the observation has standard specifications; different observations are highly comparable; can be used for comparison and verification of remote sensing retrieval results. | Low temporal and spatial resolutions; cannot satisfy the needs of ABL research; can only obtain average profile of common meteorological elements; large spatial drift; stationary and uniform atmosphere is assumed as a prerequisite. |
| Tethered balloon            | Adjustable temporal and spatial resolutions; can be regarded as a movable “soft tower” with high mobility; can carry a variety of sensors to achieve meteorological, turbulent, chemical, and remote sensing observations. | Limited temporal resolution; cannot conduct continuous observation for long periods; limited coverage for detection; difficult to apply under strong wind conditions for the slant distance is large. |
| Meteorological tower        | Continuous observation for long periods; encrypted observation of the lower atmosphere; can carry a variety of sensors to achieve meteorological, turbulent, chemical, and remote sensing observations. | Meteorological tower is high in cost; cannot be moved; height of the tower is mostly between 50 and 400 m; limited coverage for detection. |
| Aircraft                    | High temporal and spatial resolution; good spatial continuity; suitable for mesoscale synoptic research; can carry a variety of sensors to achieve meteorological, turbulent, chemical, remote sensing observations. | Limited by weather conditions and routes; cannot perform continuous observation for long periods; requires accurate measurement of flight trajectory; complicated data processing procedures. |
| Ground-based remote sensing | Aerosol lidar/ceilometer/Doppler wind lidar: High temporal and spatial resolutions; ceilometer is safe to the human eye, easy to maintain, and low in cost; all can identify the vertical distribution of aerosols. The Doppler wind lidar can also retrieve information of wind and turbulence. | Blind area issues exist in the lower atmosphere; require presence of particulate matter in the atmosphere; discrepancy between the aerosol accumulation layer and the turbulent boundary layer; difficult to retrieve the ABL due to clouds, residual layer, and multi-layer structures of aerosols. Limited accuracy under complicated weather conditions. |
| Ground-based remote sensing | Microwave radiometer: High temporal resolution; good penetrability to clouds and less disturbed by clouds. | Blind area issues exist in the lower atmosphere; vertical resolution decreases with height; retrieval error increases with height. |
| Ground-based remote sensing | Wind profiler: High temporal and spatial resolutions; information about the wind field can be retrieved; movable with high mobility. | Blind area issues exist in the lower atmosphere; limited spatial resolution; results are disturbed due to weak mixing of water vapor, clouds, or complicated weather. |
| Space-based remote sensing  | Satellite remote sensing: All-weather observation; wide spatial coverage; microwave band is less affected by clouds and precipitation. | Low accuracy of retrieval for the lower atmosphere; difficult to retrieve the lower boundary layer height; rough horizontal and vertical resolutions. |

The presence of turbulence is the essential difference between the ABL and the free atmosphere. Turbulent and non-turbulent flows can be distinguished according to the Richardson number (Ri). In practical applications, the minimum height at which Ri exceeds the critical value Ri_c is often regarded as the ABLH (Vogelezang and Holtslag, 1996; Joffre et al., 2001). The Ri method includes both dynamic and thermodynamic effects, with comprehensive consideration of the physical processes, and Ri can be easily calculated from the gradient of average quantity. However, the approach has the following problems. (1) The real atmosphere is not uniform and stationary; when calculating the gradient of meteorological elements, Ri is sensitive to the selection of vertical resolution. (2) There are considerable uncertainties in Ri_c, which may be affected by the earth’s rotation, the Brunt–Väisälä frequency (BV frequency), and surface roughness (Zilitinkevich and Baklanov, 2002; Vickers and Mahrt, 2004; Dai et al., 2014). Investigations have been made to determine a universal value of Ri_c, but according to the study of Richardson et al. (2013), Ri_c is not a constant but a function of bulk atmospheric stability. The study of Dai et al. (2014) shows that although the Ri method has a clear physical meaning, the detection rate of the stable boundary layer height is low in...
Table 2. Diagnostic formulae for estimating the ABLH

| Literature | Diagnostic formula |
|------------|--------------------|
| Based on surface fluxes | $h = 0.4 \left( \frac{u_L}{f} \right)^{1/2}$ |
| (1978) Brost and Wyngaard | $h = \frac{0.3h_s/f L}{1 + 1.9h/f L}$ |
| Nieuwstadt (1981) | $(f h/C_n u_s)^2 + h/C_L + N h + h/f L^{1/2} + h | N f | L^{1/2} = 1$ |
| San José and Casanova (1988) | $h = \frac{C_{gh}}{h} \left[ 1 + \frac{C_{gh}^2 u_s (1 + C_{gh}^2 u_s | N f | l) - 1/2}{C_{gh}^2 h/f L} \right]$ |
| Zilitinkevich and Mironov (1996) | $h = \frac{C_{gh}}{f u_s} \left[ \frac{h}{\alpha N f L} \right]^3$ |
| Zilitinkevich et al. (2002) | $h = \frac{u_s}{N} = \alpha Q^{1/2} | f | J^{3/2} | f | J^{1/4}$ |
| Steeneveld et al. (2007a) | $h = \frac{u_s}{N} = \alpha Q^{1/2} | f | J^{3/2} | f | J^{1/4}$ |
| Steeneveld et al. (2007b) | $h = \frac{u_s}{N} = \alpha Q^{1/2} | f | J^{3/2} | f | J^{1/4}$ |
| Casasanta et al. (2014) | $h = \frac{u_s}{N} = \alpha Q^{1/2} | f | J^{3/2} | f | J^{1/4}$ |
| Syrakov (2015) | $h = \frac{u_s}{N} = \alpha Q^{1/2} | f | J^{3/2} | f | J^{1/4}$ |
| Based on Richardson number | $R_{ibc} = \frac{1}{\mu} f h L^2 \left[ \ln \left( \frac{h}{z_0} \right) - C \right]$ |
| Melgarejo and Deardorff (1974) | $R_{ibc} = \frac{1}{\mu} f h L^2 \left[ \ln \left( \frac{h}{z_0} \right) - A \right] + B^2$ |
| Vogezezang and Holtslag (1996) | $R_{ib} = \frac{g}{\theta (z_1 - z_2)} \left[ \theta (z_1) - \theta (z_2) \right] \left[ v (z_1) - v (z_2) \right]^2$ |
| Vickers and Mahrt (2004) | $R_{ibc} = 0.16 \left( 10^{-7} \frac{Ro}{180} \right)^{0.18}$ |
| Richardson et al. (2013) | $R_{ibc} = \frac{\alpha}{h} f h L$ |
| Others | $h = \frac{121}{6} (6 - P) (T - T_d) + \frac{0.169 P \left( u_s + 0.257 \right)}{12 f \ln \left( \frac{z}{z_0} \right)}$ |
| China National Standard GB/T 3840-1991 (SBQTS and SEPA of China, 1991) | $h = \frac{u_L^{10}}{f}$ (Unstable or neutral); $h = \frac{\beta^{10}}{f}$ (Stable) |
| Cheng et al. (1997) | $h = \sum_{i=1}^{5} \sum_{j=1}^{8} \left[ (6 - P) \left( T - T_d \right) + \frac{0.169 P \left( u_s + 0.257 \right)}{12 f \ln \left( \frac{z}{z_0} \right)} \right] \left[ f (i, j) \right]$ |

In addition, it is difficult to accurately identify the convective boundary layer height by use of this method. The detection rate cannot be improved significantly by changing the critical value.  

4.1.3 Other diagnostic formulae

(1) The Guobiao (GB) method. According to China National Standard GB/T 3840-1991 (SBQTS and SEPA of China, 1991), the solar elevation angle, cloud cover, and wind speed observed on the ground can be used to determine the atmospheric stability, and the height of the mixed layer can be calculated according to the type of stability (see Table 2). The GB method requires only ground observation data, and can be easily implemented because it uses national standards. However, under static wind conditions, this method will result in a systematic underestimation of the boundary layer height.

(2) The Nozaki method. Nozaki et al. (1974) proposed an algorithm for estimating the ABLH using temperature, dew point, stability, wind speed, and roughness observed on the ground. Based on their study, Cheng et
al. (1997) improved the formula by considering the combined frequency of wind speed and atmospheric stability. The Nozaki method requires only ground observation data, which can be applied easily and has application value for areas without sufficient radiosonde data. It can be used to describe the diurnal variation of the boundary layer; however, the results are significantly overestimated (Du et al., 2013).

### 4.2 Forecast equations

The evolution of the boundary layer is a continuous process, with meteorological elements in the surface layer often changing significantly. However, the diagnostic boundary layer height does not reflect its continuous development. Consequently, it is more reasonable to use forecast equations.

#### 4.2.1 Forecast equations for the convective boundary layer

1. The energy balance model. Neglecting turbulent entrainment, advection, radiation, and latent heating, the energy balance model only takes thermodynamic effects into consideration. It is assumed that the sensible heat flux transported upwards from the surface is equal to the heat absorbed by the atmosphere, and the absorbed heat is used for the uplift of the mixed layer. Accordingly, the mixed layer height can be determined (Stull, 1988). This model is simplistic and can only be used for rough estimations.

2. The bulk model. It is also known as the zero-order jump model, slab model, jump model, or the integral model. It was proposed by Ball (1960) and has been continuously improved since then (Lilly, 1968; Tennekes, 1973; Zeman and Tennekes, 1977). This model neglects the thickness of the entrainment zone and the super-adiabatic layer near the surface. It assumes that the mixed layer is uniform, where the potential temperature, wind speed, and specific humidity are constant, but their values jump at the top of the boundary layer, and fluxes vary linearly with height in the mixed layer. By parameterizing the heat flux at the boundary layer top, the equations can be enclosed and a forecast equation for the mixed layer is obtained (Stull, 1988; Sheng et al., 2013). This model can estimate the development of the mixed layer better, and the calculated results are consistent with observed values.

3. The first-order jump model. Based on the zero-order jump model, Deardorff (1979) established the first-order jump model with the consideration of structure of the entrainment zone. To enclose the equations, different studies adopt different parameterizations of the entrainment zone thickness (Zhang et al., 1990). Compared with the zero-order jump model, the accuracy of estimating the mixed layer height with the first-order jump model has not been significantly improved. However, it can describe the characteristics of the entrainment zone, whose simulated thickness and potential temperature jump are more consistent with observations.

Batchvarova and Gryning (1994) presented a prognostic model suitable for neutral and convective conditions. The model combined the zero-order model proposed by Batchvarova and Gryning (1991) and the parameterization of the depth of entrainment zone proposed by Gryning and Batchvarova (1994). In application, it only requires the data of friction velocity, turbulent heat flux near the surface, and potential temperature gradient in the free atmosphere; and if the information of horizontal divergence of large-scale motion is available, the model can also take subsidence into account.

#### 4.2.2 Forecast equations for the stable boundary layer

Based on the thermal energy equation, Yamada (1979) considered the longwave radiative cooling effect and assumed that the atmosphere was horizontally homogenous with a flat terrain, and ignored the horizontal/vertical transport terms. The empirical formula of the local potential temperature profile in the stable boundary layer was fitted from observations, which was used to simplify the model, and the forecast equation for the stable boundary layer was then obtained. In the application, it is necessary to fit the local expression of the potential temperature and re-establish the forecast equation applicable to the local area (Liu et al., 1985).

According to the source and sink term of TKE in the stable boundary layer, Nieuwstadt and Tennekes (1981) defined a new Richardson number ($\text{Ri}_R$) using the ratio of production term and dissipation term of TKE. The rate equation is then obtained by substituting the governing equation into the numerator/denominator of $\text{Ri}_R$. The forecast equation is in the form of linear relaxation equations, and its solution tends to be an equilibrium value. The equilibrium height is related to the work done by ageostrophic wind in the ABL. The timescale of relaxation process lasts approximately 10 h after sunset, demonstrating the slow development of the stable boundary layer. It should be noted that this equation can only describe the stable boundary layer a few hours after sunset, and it is not applicable during the transition from day to night when the atmosphere is extremely non-stationary.

Zeman (1979) proposed a forecast equation for the stable boundary layer by integrating the momentum equation. This model is in line with the Brost–Wyngaard model (Brost and Wyngaard, 1978). However, it re-
quires data for the difference between the wind speed at a certain height and the average wind speed in the boundary layer, which cannot be obtained by conventional observation, thereby limiting its application.

Gassmann and Mazzeo (2001) put forward a prognostic equation for nocturnal stable boundary based on the heat conservation equation. The equation requires information of surface cooling rate and vertical kinematic turbulent heat flux. It is suitable for studying nighttime ABLs with low wind speed and less cloud. Zilitinkevich et al. (2002) considered the influence of synoptic-scale vertical motion and proposed a relaxation equation to forecast the stable ABLH. Based on this prognostic equation, Zilitinkevich and Bakanov (2002) further complemented the consideration of sub-grid scale horizontal motion and replaced the original equilibrium height by a corrected quasi-equilibrium height, further improving the prognostic equation of the stable boundary layer.

5. Conclusions and future perspectives

From the perspective of atmospheric turbulence, the top of the ABL is the boundary between turbulent and non-turbulent flows, and ABLH is an important parameter reflecting the position of this boundary. Given the difficulty in obtaining the vertical distribution of turbulence parameters, the ABLH is often estimated based on thermodynamic effects, dynamic effects, and distribution of substance in practical applications. Currently, there are two main approaches to obtain the ABLH. One is to determine the height from profiles of meteorological elements based on observation, and the other is to calculate the height through parameterization.

In terms of observation, the methods for determining the ABLH can be categorized into two groups. The first group uses radiosondes, tethered balloons, meteorological towers, aircraft, or other instruments to directly observe turbulence, particulate matter, and meteorological elements, such as temperature, humidity, and wind speed, to obtain the structure of boundary layer. The second group uses remote sensing technologies to retrieve the vertical distribution of meteorological elements. Ground-based remote sensing instruments such as lidar, ceilometer, microwave radiometer, sodar, and wind profiler have been widely used for the detection of the boundary layer, and satellite remote sensing is emerging as increasingly important in the field. The accuracy of the data obtained by direct observation is higher than remote sensing, while remote sensing technologies provide continuous observation for the boundary layer. The two groups complement each other and are indispensable in the study of ABL. However, the ABLH determined from observation lacks temporal and spatial representativeness. Moreover, the comparability between the different observations is poor, considering the lack of systematic evaluation of different methods and the lack of standard specifications for determining the boundary layer height.

The parameterization method can determine the ABLH with only a small amount of data. It is easy to use and has a great value in places without sufficient observations. In general, forecast equations can reflect the development of the boundary layer better than diagnostic formulae. The boundary layer height in daytime is mainly affected by thermal turbulence, mechanical turbulence, and entrainment at the top of the boundary layer. Considering the above factors, the forecast equations can describe the development of mixed layer well. The situation is more complicated at night, for the development of stable boundary layer may be affected by various factors, such as radiative cooling, gravity waves, nighttime drainage wind, inertial oscillation, and intermittent turbulence. As a consequence, the accuracy of parameterization of stable boundary layer is relatively low. Therefore, it is advised to do further research on the physical mechanism of stable boundary layer and establish more comprehensive parameterization schemes.

It is well known that turbulence is a worldwide scientific problem. The theory of atmospheric turbulence lays the foundation for research on the ABL. The development of the subject on ABL relies on the development of atmospheric turbulence research, especially the theoretical breakthroughs and innovative methodologies in the field of atmospheric turbulence. However, the difficult and slow progress in atmospheric turbulence studies has significantly restricted the research development on the ABL, including the accurate determination of the ABLH. In order to accurately determine the ABLH, it is necessary to make progress in various areas regarding the theory of atmospheric turbulence, observational methods, and data analysis techniques in the future.

In terms of observation, it is recommended to conduct intensive observations of the boundary layer and make full advantages of remote sensing for continuous observations. (1) It is important to clearly understand the theoretical basis for determining the ABLH with different remote sensing approaches and to specify the theoretical basis and limitations under various conditions. For example, when lidar is used to determine the boundary layer height, the aerosol accumulation layer should be clearly distinguished from the turbulent boundary layer. (2) Furthermore, the retrieval techniques need to be fur-
ther improved. On the one hand, it is beneficial to improve the quality of data retrieved by remote sensing, promote the comparative analysis between results from remote sensing retrieval and conventional observations, and establish methods for correcting retrieved results. On the other hand, different ABLH retrieval algorithms should be comprehensively evaluated and improved to gradually increase the retrieval accuracy of the boundary layer height under complex atmospheric conditions such as clouds and residual layer. (3) It is also suggested to establish observation specifications for various observational methods, to establish technical specifications for determining the boundary layer height with different methods, so that the comparability of data can be enhanced.

Moreover, it is recommended to integrate a variety of observations, information, and methods for the analysis of ABLH. For example, traditional observation and remote sensing methods can be combined to interpolate the blind areas of remote sensing instruments in the surface layer. The ABLH can be determined by using complementary approaches from different perspectives to produce comprehensive results. For example, combining the RASS system, lidar, and microwave radiometer can make up for the disadvantages and uncertainties in each method. The turbulent exchange between surface and atmosphere is closely related to the development of the ABL. Therefore, the boundary layer height can be determined by using a combination of high-altitude observations and surface meteorological and turbulence observations.

In recent years, many mathematical tools are popular in the field of signal processing, such as wavelet analysis, image edge detection, and extended Kalman filter. Good mathematical tools are valuable resources for research, and it should be attached importance to the application of mathematical tools for the determination of the boundary layer height in the future.

REFERENCES
Angevine, W. M., A. B. White, and S. K. Avery, 1994: Boundary-layer depth and entrainment zone characterization with a boundary-layer profiler. Bound.-Layer Meteor., 68, 375–385, doi: 10.1007/BF00706797.
Ao, C. O., D. E. Waliser, S. K. Chan, et al., 2012: Planetary boundary layer heights from GPS radio occultation refractivity and humidity profiles. J. Geophys. Res. Atmos., 117, D16117, doi: 10.1029/2012JD017598.
Ball, F. K., 1960: Control of inversion height by surface heating. Quart. J. Roy. Meteor. Soc., 86, 483–494, doi: 10.1002/qj.49708637005.
Banta, R. M., Y. L. Pichugina, and W. A. Brewer, 2006: Turbulent velocity–variance profiles in the stable boundary layer generated by a nocturnal low-level jet. J. Atmos. Sci., 63, 2700–2719, doi: 10.1175/JAS3776.1.
Barlow, J. F., T. M. Dunbar, E. G. Nemitz, et al., 2011: Boundary layer dynamics over London, UK, as observed using Doppler lidar during REPARTEE-II. Atmos. Chem. Phys., 11, 2111–2125, doi: 10.5194/acp-11-2111-2011.
Batchvarova, E., and S.-E. Gryning, 1991: Applied model for the growth of the daytime mixed layer. Bound.-Layer Meteor., 56, 261–274, doi: 10.1007/BF00120423.
Batchvarova, E., and S.-E. Gryning, 1994: An applied model for the height of the daytime mixed layer and the entrainment zone. Bound.-Layer Meteor., 71, 311–323, doi: 10.1007/bf00713744.
Beyrich, F., 1995: Mixing-height estimation in the convective boundary layer using sodar data. Bound.-Layer Meteor., 74, 1–18, doi: 10.1007/bf00715708.
Beyrich, F., 1997: Mixing height estimation from sodar data—A critical discussion. Atmos. Environ., 31, 3941–3953, doi: 10.1016/s1352-2310(97)00231-8.
Bravo-Aranda, J. A., G. De Arruda Moreira, F. Navas-Guzmán, et al., 2017: A new methodology for PBL height estimations based on lidar depolarization measurements: Analysis and comparison against MWR and WRF model-based results. Atmos. Chem. Phys., 17, 6839–6851, doi: 10.5194/acp-17-6839-2017.
Brost, R. A., and J. C. Wyngaard, 1978: A model study of the stably stratified planetary boundary layer. J. Atmos. Sci., 35, 1427–1440, doi: 10.1175/1520-0469(1978)035<1427:AMSOS>2.0.CO;2.
Caicedo, V., B. Rappenglück, B. Lefer, et al., 2017: Comparison of aerosol lidar retrieval methods for boundary layer height detection using ceilometer aerosol backscatter data. Atmos. Meas. Tech., 10, 1609–1622, doi: 10.5194/amt-10-1609-2017.
Casasanta, G., I. Pietroni, I. Petenko, et al., 2014: Observed and modelled convective mixing-layer height at Dome C, Antarctica. Bound.-Layer Meteor., 151, 597–608, doi: 10.1007/s10546-014-9907-5.
Chanin, M. L., A. Garnier, A. Hauchecorne, et al., 1989: A Doppler lidar for measuring winds in the middle atmosphere. Geophys. Res. Lett., 16, 1273–1276, doi: 10.1029/GL016i011p01273.
Cheng, S. Y., D. L. Xi, B. N. Zhang, et al., 1997: Study on the determination and calculating method of atmospheric mixing layer height. China Environ. Sci., 17, 512–516. (in Chinese)
Cohn, S. A., and W. M. Angevine, 2000: Boundary layer height and entrainment zone thickness measured by lidars and wind-profiling radars. J. Appl. Meteor., 39, 1233–1247, doi: 10.1175/1520-0450(2000)039<1233:bhaeae>2.0.co;2.
Collaud Coen, M., C. Praz, A. Haefele, et al., 2014: Determination and climatology of the planetary boundary layer height above the Swiss plateau by in situ and remote sensing measurements as well as by the COSMO-2 model. Atmos. Chem. Phys., 14, 13205–13221, doi: 10.5194/acp-14-13205-2014.
Collis, R. T. H., and M. G. H. Ligda, 1964: Laser radar echoes from the clear atmosphere. Nature, 203, 508, doi: 10.1038/203508a0.
Collis, R. T. H., F. G. Feinhard, and M. G. H. Ligda, 1964: Laser radar echoes from a stratified clear atmosphere. Nature, 203,
1274–1275, doi: 10.1038/2031274a0.

Dai, C., Q. Wang, J. A. Kalogiros, et al., 2014: Determining boundary-layer height from aircraft measurements. Bound.-Layer Meteor., 152, 277–302, doi: 10.1007/s10546-014-9929-z.

Davis, K. J., N. Gamage, C. R. Hagelberg, et al., 2000: An objective method for deriving atmospheric structure from airborne lidar observations. J. Atmos. Oceanic Technol., 17, 1455–1468, doi: 10.1175/1520-0426(2000)017<1455:AOMFDA>2.0.CO;2.

de Arruda Moreira, G., M. T. A. Marques, W. Nakaema, et al., 2015: Planetary boundary layer height estimation from Doppler wind lidar measurements, radiosonde and hysplit model comparison. Opt. Pura Y Apl., 48, 179–183, doi: 10.7149/OPA.48.3.179.

de Arruda Moreira, G., J. L. Guerrero-Rascado, J. A. Bravo-Arruda, et al., 2018: Study of the planetary boundary layer by microwave radiometer, elastic lidar and Doppler lidar estimations in Southern Iberian Peninsula. Atmos. Res., 213, 185–195, doi: 10.1016/j.atmosres.2018.06.007.

Deardorff, J. W., 1979: Prediction of convective mixed-layer entrainment for realistic capping inversion structure. J. Atmos. Sci., 36, 424–436, doi: 10.1175/1520-0469(1979)036<0424:POCMLI>2.0.CO;2.

Deng, T., D. Wu, X. J. Deng, et al., 2014: A vertical sounding of severe haze process in Guangzhou area. Sci. China Earth Sci., 57, 2650–2656, doi: 10.1007/s11430-014-4928-y.

Ding, A. J., C. B. Fu, X. Q. Yang, et al., 2013: Intense atmospheric pollution modifies weather: A case of mixed biomass burning with fossil fuel combustion pollution in eastern China. Atmos. Chem. Phys., 13, 10545–10554, doi: 10.5194/acp-13-10545-2013.

Du, C. L., S. Y. Liu, X. Yu, et al., 2013: Urban boundary layer height characteristics and relationship with particulate matter mass concentrations in Xi’an, central China. Aerosol Air Qual. Res., 13, 1598–1607, doi: 10.4209/aair.2012.10.0274.

Emeis, S., and M. Türk, 2004: Frequency distributions of the mixing height over an urban area from SODAR data. Meteor. Z., 13, 361–367, doi: 10.1127/0941-2948/2004/0013-0361.

Emeis, S., and K. Schäfer, 2006: Remote sensing methods to investigate boundary-layer structures relevant to air pollution in cities. Bound.-Layer Meteor., 121, 377–385, doi: 10.1007/s10546-006-9068-2.

Emeis, S., K. Schäfer, and C. Münkel, 2008: Surface-based remote sensing of the mixing-layer height—A review. Meteor. Z., 17, 621–630, doi: 10.1007/s00757-008-0312.

Eresmaa, N., A. Karppinen, S. M. Joffre, et al., 2006: Mixing height determination by ceilometer. Atmos. Chem. Phys., 6, 1485–1493, doi: 10.5194/acp-6-1485-2006.

Fairall, C. W., 1991: The humidity and temperature sensitivity of clear-air radars in the convective boundary layer. J. Appl. Meteor., 30, 1064–1074, doi: 10.1175/1520-0450(1991)030<1064:HTSOSA>2.0.CO;2.

Fan, S. H., Z. Q. Gao, J. Kalogiros, et al., 2019: Estimate of boundary-layer depth in Nanjing city using aerosol lidar data during 2016–2017 winter. Atmos. Environ., 205, 67–77, doi: 10.1016/j.atmosenv.2019.02.022.

Flamant, C., J. Pelon, P. H. Flamant, et al., 1997: Lidar determination of the entrainment zone thickness at the top of the unstable marine atmospheric boundary layer. Bound.-Layer Meteor., 83, 247–284, doi: 10.1023/a:1000258318944.

Friedrich, K., J. K. Lundquist, M. Aitken, et al., 2012: Stability and turbulence in the atmospheric boundary layer: A comparison of remote sensing and tower observations. Geophys. Res. Lett., 39, L03801, doi: 10.1029/2011gl050413.

Gao, D. Y., 1994: Advance in studying air/sea exchange and air/sea boundary layer observation. Prog. Geophys., 9, 111–118. (in Chinese)

Garratt, J. R., 1994: Review: The atmospheric boundary layer. Earth-Sci. Rev., 37, 89–134, doi: 10.1016/0012-8252(94)9026-4.

Gassmann, M. I., and N. A. Mazzeo, 2001: Nocturnal stable boundary layer height model and its application. Atmos. Res., 57, 247–259, doi: 10.1016/S0169-8095(01)00072-2.

Ge, S. R., 2017: Research on vertical air velocity and planetary boundary height detection by the wind profiler. Master dissertation, National University of Defense Technology, Changsha, China. 75 pp, doi:10.27052/d.cnki.gzjgu.2017.009916. (in Chinese)

Grynning, S.-E., and E. Batchvarova, 1994: Parametrization of the depth of the entrainment zone above the daytime mixed layer. Quart. J. Roy. Meteor. Soc., 120, 47–58, doi: 10.1002/qj.4972051505.

Gui, K., H. Z. Che, Y. Q. Wang, et al., 2019: Satellite-derived PM2.5 concentration trends over eastern China from 1998 to 2016: Relationships to emissions and meteorological parameters. Environ. Pollut., 247, 1125–1133, doi: 10.1016/j.envpol.2019.01.056.

Haefelin, M., F. Angelini, Y. Morille, et al., 2012: Evaluation of mixing-height retrievals from automatic profiling lidars and ceilometers in view of future integrated networks in Europe. Bound.-Layer Meteor., 143, 49–75, doi: 10.1007/s10546-011-9643-z.

Han, B., C. L. Zhao, S. H. Lü, et al., 2015: A diagnostic analysis on the effect of the residual layer in convective boundary layer development near Mongolia using 20th century reanalysis data. Adv. Atmos. Sci., 32, 807–820, doi: 10.1007/s00376-014-4164-6.

He, Q. S., J. T. Mao, J. Y. Chen, et al., 2006: Observational and modeling studies of urban atmospheric boundary-layer height and its evolution mechanisms. Atmos. Environ., 40, 1064–1077, doi: 10.1016/j.atmosenv.2005.11.016.

Hennemuth, B., and A. Lammert, 2006: Determination of the atmospheric boundary layer height from radiosonde and lidar backscatter. Bound.-Layer Meteor., 120, 181–200, doi: 10.1007/s10546-005-9035-3.

Hewison, T. J., 2006: Profiling temperature and humidity by ground-based microwave radiometers. Ph.D. dissertation, University of Reading, Reading, Berkshire, UK, 292 pp.

Holzworth, G. C., 1964: Estimates of mean maximum mixing depths in the contiguous United States. Mon. Wea. Rev., 92, 235–242, doi: 10.1175/1520-0493(1964)092<0235:EOMMMD>2.3.CO;2.

Hooper, W. P., and E. W. Eloranta, 1986: Lidar measurements of wind in the planetary boundary layer: The method, accuracy and results from joint measurements with radiosonde and kypton. J. Climate Appl. Meteor., 25, 990–1001, doi: 10.1175/1520-0450(1986)025<0990:LMOWIT>2.0.CO;2.

Hu, M. B., and M. Y. Li, 2010: The development and technological
status of wind profiling radar. *Sci. Meteor. Sinica*, **30**, 724–729, doi: 10.3969/j.issn.1009-0827.2010.05.021. (in Chinese)

Huang, M., Z. Q. Gao, S. G. Miao, et al., 2017: Estimate of boundary-layer depth over Beijing, China, using Doppler lidar data during SURF-2015. *Bound.-Layer Meteor.*, **162**, 503–522, doi: 10.1007/s10546-016-0205-2.

Hyun, Y. K., K. E. Kim, and K. J. Ha, 2005: A comparison of methods to estimate the height of stable boundary layer over a temperate grassland. *Agric. For. Meteor.*, **132**, 132–142, doi: 10.1016/j.agrformet.2005.03.010.

Joffre, S. M., M. Kangas, M. Heikinheimo, et al., 2001: Variability of the stable and unstable atmospheric boundary layer height and its scales over a boreal forest. *Bound.-Layer Meteor.*, **99**, 429–450, doi: 10.1023/a:1018956525605.

Kallistratova, M. A., I. V. Petenko, R. D. Kouznetso, et al., 2018: Sounding of the atmospheric boundary layer: Review of studies at the Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences. *Izv. Atmos. Ocean. Phys.*, **54**, 242–256, doi: 10.1134/S0001433818030088.

Khaykin, S. M., A. Hauchecorne, J. Porteneuve, et al., 2016: Ground-based Rayleigh–Mie Doppler lidar for wind measurements in the middle atmosphere. *EPJ Web Conf.*, **119**, 13005, doi: 10.1051/epjconf/201611913005.

Kim, D. K., and D. I. Lee, 2015: Atmospheric thickness and vertical structure properties in wintertime precipitation events from microwave radiometer, radiosonde and wind profiler observations. *Meteor. Appl.*, **22**, 599–609, doi: 10.1002/met.1494.

Kosović, B., and J. A. Curry, 2000: A large eddy simulation study of a quasi-steady, stably stratified atmospheric boundary layer. *J. Atmos. Sci.*, **57**, 1052–1068, doi: 10.1175/1520-0469(2000)057<1052:aless>2.0.co;2.

Kothaush, S., and C. S. B. Grimmel, 2018: Atmospheric boundary-layer characteristics from ceilometer measurements. Part 1: A new method to track mixed layer height and classify clouds. *Quart. J. Roy. Meteor. Soc.*, **144**, 1525–1538, doi: 10.1002/qj.3299.

Kursinski, E. R., G. A. Hajj, W. I. Bertiger, et al., 1996: Initial results of radio occultation observations of earth’s atmosphere using the global positioning system. *Science*, **271**, 1107–1110, doi: 10.1126/science.271.5252.1107.

Lange, D., J. Tiana-Alsina, U. Saeed, et al., 2014: Atmospheric boundary layer height monitoring using a Kalman filter and backscatter lidar returns. *IEEE Trans. Geosci. Remote Sens.*, **52**, 4717–4728, doi: 10.1109/tgrs.2013.2284110.

LeMone, M. A., M. Tewari, F. Chen, et al., 2014: Objectively determined fair-weather NBL features in ARW-WRF and their comparison to CASES-97 observations. *Mon. Wea. Rev.*, **142**, 2709–2732, doi: 10.1175/mwr-d-13-00358.1.

Lewis, J. R., E. J. Welton, A. M. Molod, et al., 2013: Improved boundary layer depth retrievals from MPLNET. *J. Geophys. Res. Atmos.*, **118**, 9870–9879, doi: 10.1002/jgrd.50570.

Li, H., Y. Yang, X. M. Hu, et al., 2017: Evaluation of retrieval methods of daytime convective boundary layer height based on lidar data. *J. Geophys. Res. Atmos.*, **122**, 4578–4593, doi: 10.1002/2016JD025620.

Li, Q. H., B. G. Wu, J. L. Liu, et al., 2020a: Characteristics of the atmospheric boundary layer and its relation with PM2.5 during haze episodes in winter in the North China Plain. *Atmos. Environ.*, **223**, 117265, doi: 10.1016/j.atmosenv.2020.117265.

Li, Q. H., H. S. Zhang, T. T. Ju, et al., 2020b: Experimental research on the characteristics of the atmospheric boundary layer in the semi-arid North China. *Acta Sci. Nat. Univ. Pekinensis*, **56**, 215–222, doi: 10.13209/j.issn.1006-9895.1710.17173. (in Chinese)

Li, X., J. N. Quan, F. Wang, et al., 2018: Evaluation of the method for planetary boundary layer height retrieval by lidar and its application in Beijing. *Chinese J. Atmos. Sci.*, **42**, 435–446, doi: 10.3878/j.issn.1006-9895.1802.17274. (in Chinese)

Li, Z. Q., J. P. Guo, A. J. Ding, et al., 2017: Aerosol and boundary-layer interactions and impact on air quality. *Natil. Sci. Rev.*, **4**, 810–833, doi: 10.1093/ndr/nwx117.

Lilly, D. K., 1968: Models of cloud-topped mixed layers under a strong inversion. *Quart. J. Roy. Meteor. Soc.*, **94**, 292–309, doi: 10.1002/qj.49709440106.

Liu, B. M., Y. Y. Ma, W. Gong, et al., 2018: Determination of boundary layer top on the basis of the characteristics of atmospheric particles. *Atmos. Environ.*, **178**, 140–147, doi: 10.1016/j.atmosenv.2018.01.054.

Liu, C., Y. Z. Li, and R. B. Jiang, 1985: A simple model for predicting the inversion layer height in the stable boundary layer. *Meteor. Mon.*, **11**, 31–33. (in Chinese)

Liu, H. Y., 2011: The temperature profile comparison between the ground-based microwave radiometer and the other instrument for the recent three years. *Acta Meteor. Sinica*, **69**, 719–728, doi: 10.11676/qxxb2011.063. (in Chinese)

Liu, H. Z., L. Wang, and Q. Du, 2018: An overview of recent studies on atmospheric boundary layer physics at LAPC (2012–2017). *Chinese J. Atmos. Sci.*, **42**, 823–832, doi: 10.3878/j.issn.1006-9895.1802.17274. (in Chinese)

Liu, J. Z., and Q. Zhang, 2010: Evaluation and analysis of retrieval products of ground-based microwave radiometer. *Meteor. Sci. Technol.*, **38**, 325–331, doi: 10.19517/j.1671-6345.2010.03.011. (in Chinese)

Liu, S. Y., and X. Z. Liang, 2010: Observed diurnal cycle climatology of planetary boundary layer height. *J. Climate*, **23**, 5790–5809, doi: 10.1175/2010JCLI3552.1.

Liu, X. H., and E. Ohtaki, 1997: An independent method to determine the height of the mixed layer. *Bound.-Layer Meteor.*, **85**, 497–504, doi: 10.1023/A:100051030752.

Ma, M. J., Z. X. Pu, S. G. Wang, et al., 2011: Characteristics and numerical simulations of extremely large atmospheric boundary-layer heights over an arid region in Northwest China. *Bound.-Layer Meteor.*, **140**, 163–176, doi: 10.1007/s10546-011-9608-2.

Mahrt, L., R. C. Heald, D. H. Lenschow, et al., 1979: An observational study of the structure of the nocturnal boundary layer. *Bound.-Layer Meteor.*, **17**, 247–264, doi: 10.1007/bf00117983.

Marsham, J. H., D. J. Parker, C. M. Grim, et al., 2008: Observations of mesoscale and boundary-layer scale circulations affecting dust transport and uplift over the Sahara. *Atmos. Chem. Phys.*, **8**, 6979–6993, doi: 10.5194/acp-8-6979-2008.

Melfi, S. H., J. D. Spinhomme, S. H. Chou, et al., 1985: Lidar observations of vertically organized convection in the planetary boundary layer over the ocean. *J. Climate Appl. Meteor.*, **24**, 806–821, doi: 10.1175/1520-0450(1985)024<0806:LOOVOC>2.0.CO;2.

Melgarejo, J. W., and J. W. Deardorff, 1974: Stability functions
for the boundary-layer resistance laws based upon observed boundary-layer heights. J. Atmos. Sci., 31, 1324–1333, doi: 10.1175/1520-0469(1974)031<1324:sfblbr>2.0.co;2.

Menut, L., C. Flamant, J. Pelon, et al., 1999: Urban boundary-layer height determination from lidar measurements over the Paris area. Appl. Opt., 38, 945–954, doi: 10.1364/ao.38.000945.

Münkel, C., and J. Räsänen, 2004: New optical concept for commercial lidar ceilometers scanning the boundary layer. Proc. SPIE Remote Sensing of Clouds and the Atmosphere IX, SPIE, Maspalomas, Canary Islands, Spain, 364–374, doi: 10.1117/12.565540.

Nieuwstadt, F. T. M., 1981: The steady-state height and resistance laws of the nocturnal boundary layer: Theory compared with cabauw observations. Bound.-Layer Meteor., 20, 3–17, doi: 10.1007/bf00119920.

Nieuwstadt, F. T. M. and H. Tennekes, 1981: A rate equation for the nocturnal boundary-layer height. J. Atmos. Sci., 38, 1418–1428, doi: 10.1175/1520-0469(1981)038<1418:aretnb>2.0.co;2.

Nozaki, K. Y., 1974: Mixing depth model using hourly surface observations. Bull. Amer. Meteor. Soc., 55, 867–867.

O’Connor, E. J., A. J. Illingworth, I. M. Brooks, et al., 2010: A method for estimating the turbulent kinetic energy dissipation rate from a vertically pointing Doppler lidar, and independent evaluation from balloon-borne in situ measurements. J. Atmos. Oceanic Technol., 27, 1652–1664, doi: 10.1175/2010JTECHA1455.1.

Pearson, G., F. Davies, and C. Collier, 2010: Remote sensing of the tropical rain forest boundary layer using pulsed Doppler lidar. Atmos. Chem. Phys., 10, 5891–5901, doi: 10.5194/acp-10-5891-2010.

Peng, J., C. S. B. Grimmond, X. S. Fu, et al., 2017: Ceilometer-based analysis of Shanghai’s boundary layer height (under rain- and fog-free conditions). J. Atmos. Oceanic Technol., 34, 749–764, doi: 10.1175/JTECH-D-16-0132.1.

Poltera, Y., G. Martucci, M. Collaud Coen, et al., 2017: PathfinderTURB: An automatic boundary layer algorithm development, validation and application to study the impact on in situ measurements at the Jungfraujoch. Atmos. Chem. Phys., 17, 10051–10070, doi: 10.5194/acp-17-10051-2017.

Qu, Y. W., Y. Han, Y. H. Wu, et al., 2017: Study of PBLH and its correlation with particulate matter from one-year observation over Nanjing, Southeast China. Remote Sens., 9, 668, doi: 10.3390/rs9070668.

Quan, J. N., Y. Gao, Q. Zhang, et al., 2013: Evolution of planetary boundary layer under different weather conditions, and its impact on aerosol concentrations. Particuology, 11, 34–40, doi: 10.1016/j.partic.2012.04.005.

Quan, J. N., Y. J. Dou, X. J. Zhao, et al., 2020: Regional atmospheric pollutant transport mechanisms over the North China Plain driven by topography and planetary boundary layer processes. Atmos. Environ., 221, 117098, doi: 10.1016/j.atmosenv.2019.117098.

Raman, S., B. Templeman, S. Templeman, et al., 1990: Structure of the Indian southwesterly pre-monsoon and monsoon boundary layers: Observations and numerical simulation. Atmos. Environ., 24, 723–734, doi: 10.1016/0960-1686(90)90027-3.

Ren, Y., H. S. Zhang, W. Wei, et al., 2019a: Effects of turbulence structure and urbanization on the heavy haze pollution process. Atmos. Chem. Phys., 19, 1041–1057, doi: 10.5194/acp-19-1041-2019.

Ren, Y., H. S. Zhang, W. Wei, et al., 2019b: A study on atmospheric turbulence structure and intermittency during heavy haze pollution in the Beijing area. Sci. China Earth Sci., 62, 2058–2068, doi: 10.1007/s11430-019-9451-0.

Richardson, H., S. Basu, and A. A. M. Holtslag, 2013: Improving stable boundary-layer height estimation using a stability-dependent critical bulk Richardson number. Bound.-Layer Meteor., 148, 93–109, doi: 10.1007/s10546-013-9812-3.

Russell, P. B., E. E. Utne, F. L. Ludvig, et al., 1974: A comparison of atmospheric structure as observed with monostatic acoustic sounder and lidar techniques. J. Geophys. Res. Atmos., 79, 5555–5566, doi: 10.1029/jc079i036p05555.

Saeed, U., F. Rocadenbosch, and S. Crewell, 2016: Adaptive estimation of the stable boundary layer height using combined lidar and microwave radiometer observations. IEEE Trans. Geosci. Remote Sens., 54, 6895–6906, doi: 10.1109/tgrs.2016.2586298.

San José, R., and J. Casanova, 1988: An empirical method to evaluate the height of the convective boundary layer by using small mast measurements. Atmos. Res., 22, 265–273, doi: 10.1016/0169-8095(88)90021-x.

Saraiva, L., and N. Krusche, 2013: Estimation of the boundary layer height in the southern region of Brazil. Amer. J. Environ. Eng., 3, 63–70, doi: 10.5923/j.aje20130301.09.

Sawyer, V., and Z. Q. Li, 2013: Detection, variations and inter-comparison of the planetary boundary layer depth from radiosonde, lidar and infrared spectrometer. Atmos. Environ., 79, 518–528, doi: 10.1016/j.atmosenv.2013.07.019.

Schween, J. H., A. Hirsikko, U. Löhnert, et al., 2014: Mixing-layer height retrieval with ceilometer and Doppler lidar: From case studies to long-term assessment. Atmos. Meas. Tech., 7, 3685–3704, doi: 10.5194/amt-7-3685-2014.

Seibert, P., F. Beyrich, S. E. Gryning, et al., 2000: Comparison of operational methods for the determination of the mixing height. Atmos. Environ., 12, 1001–1027, doi: 10.1016/s0004-6981(99)00349-0.

Seidel, D. J., C. O. Ao, and K. Li, 2010: Estimating climatological planetary boundary layer heights from radiosonde observations: Comparison of methods and uncertainty analysis. J. Geophys. Res. Atmos., 115, D16113, doi: 10.1029/2009JD016360.

Shen, J., L. H. Shen, X. Han, et al., 2017: Combined observation of boundary layer using lidar and microwave radiometer in Suzhou. Meteor. Sci. Technol., 45, 425–429, doi: 10.19517/j.1671-6345.20160252. (in Chinese)

Sheng, P. X., J. T. Mao, J. G. Li, et al., 2013: Atmospheric Physics. Peking University Press, Beijing, 243-275. (in Chinese)

Shi, Y., F. Hu, G. Q. Fan, et al., 2019a: Comparative analysis of the atmospheric boundary layer structure of a red-alert haze episode in Beijing. Atmos. Meas. Tech., 12, 4887–4901, doi: 10.5194/amt-12-4887-2019.

Shi, Y., F. Hu, W. C. Ding, et al., 2019b: Comparative analysis of
planetary-boundary-layer height based on aerosol lidar and radiosonde. Climatic Environ. Res., 24, 650–662, doi: 10.3878/j.issn.1006-9585.2019.19051. (in Chinese)

Shukla, K. K., D. V. Phanikumar, R. K. Newsom, et al., 2014: Estimation of the mixing layer height over a high altitude site in Central Himalayan region by using Doppler lidar. J. Atmos. Sol.-Terr. Phys., 109, 48–53, doi: 10.1016/j.jastp.2014.01.006.

Song, X. Z., H. S. Zhang, X. J. Liu, et al., 2006: Determination of atmospheric boundary layer height in unstable conditions over the middle Tibetan Plateau. Acta Sci. Nat. Univ. Pekinensis, 42, 328–333, doi: 10.13209/j.0479-8023.2006.062. (in Chinese)

State Bureau of Quality and Technical Supervision (SBQTS) and State Environmental Protection Administration (SEPA) of China, 1991: GB/T 3840-1991: Technical methods for making local emission STANDARDs of air pollutants. Standards Press of China, Beijing, 1–17. (in Chinese)

Steeneveld, G. J., B. J. H. van de Wiel, and A. A. M. Holtslag, 2007a: Diagnostic equations for the stable boundary layer height: Evaluation and dimensional analysis. J. Appl. Meteor. Climatol., 46, 212–225, doi: 10.1175/jamc2454.1.

Steeneveld, G. J., B. J. H. van de Wiel, and A. A. M. Holtslag, 2007b: Comments on deriving the equilibrium height of the stable boundary layer. Quart. J. Roy. Meteor. Soc., 133, 261–264, doi: 10.1002/qj.26.

Steyn, D. G., M. Baldi, and R. M. Hoff, 1999: The detection of mixed layer depth and entrainment zone thickness from lidar backscatter profiles. J. Atmos. Oceanic Technol., 16, 953–959, doi: 10.1175/1520-0426(1999)016<0953:TDOML>2.0.CO;2.

Stull, R. B., 1988: An Introduction to Boundary Layer Meteorology. Springer, Dordrecht, 1–545, doi: 10.1007/978-0-3027-9.

Su, T. N., Z. Q. Li, and R. Kahn, 2020: A new method to retrieve the diurnal variability of planetary boundary layer height from lidar under different thermodynamic stability conditions. Remote Sens. Environ., 237, 111519, doi: 10.1016/j.rse.2019.111519.

Syrakov, E., 2015: General diagnostic equations and regime analysis for the height of the planetary boundary layer. Quart. J. Roy. Meteor. Soc., 141, 2869–2879, doi: 10.1002/qj.2570.

Tennekes, H., 1973: A model for the dynamics of the inversion above a convective boundary layer. J. Atmos. Sci., 30, 558–567, doi: 10.1175/1520-0469(1973)030<0558:AMFTDO>2.0.CO;2.

Tsaknakis, G., A. Papayannis, P. Kokkalis, et al., 2011: Inter-comparison of lidar and ceilometer retrievals for aerosol and planetary boundary layer profiling over Athens, Greece. Atmos. Meas. Tech., 4, 1261–1273, doi: 10.5194/amt-4-1261-2011.

Tucker, S. C., C. J. Senff, A. M. Weickmann, et al., 2009: Doppler lidar estimation of mixing height using turbulence, shear, and aerosol profiles. J. Atmos. Oceanic Technol., 26, 673–688, doi: 10.1175/2008JTECHA1157.1.

Utke, E., 1972: Lidar observations of the urban aerosol structure. Bull. Amer. Meteor. Soc., 53, 358–360, doi: 10.1175/1520-0477-53.4.358.

Vickers, D., and L. Mahrt, 2004: Evaluating formulations of stable boundary layer height. J. Appl. Meteor., 43, 1736–1749, doi: 10.1175/jam2160.1.

Vogelezang, D. H. P., and A. A. M. Holtslag, 1996: Evaluation and model impacts of alternative boundary-layer height formulations. Bound.-Layer Meteor., 81, 245–269, doi: 10.1007/bf02430331.

Wang, L., C. B. Xie, Y. Han, et al., 2012: Comparison of retrieval methods of planetary boundary layer height from lidar data. J. Atmos. Environ. Opt., 7, 241–247, doi: 10.3969/j.issn.1673-6141.2012.04.001. (in Chinese)

Wang, X. L., and W. Y. Xiong, 1993: Turbulence and thickness of ecoboundary layer. J. Nanjing For. Univ., 17, 9–15, doi: 10.3969/j.issn.1000-2006.1993.01.002. (in Chinese)

Wang, Z., X. Cao, L. Zhang, et al., 2012: Lidar measurement of planetary boundary layer height and comparison with microwave profiling radiometer observation. Atmos. Meas. Tech., 5, 1965–1972, doi: 10.5194/amt-5-1965-2012.

Wei, W., H. S. Zhang, X. H. Cai, et al., 2020: Influence of intermittent turbulence on air pollution and its dispersion in winter 2016/2017 over Beijing, China. J. Meteor. Res., 34, 176–188, doi: 10.1007/s13351-020-9128-4.

White, A. B., C. J. Senff, and R. M. Banta, 1999: A comparison of mixing depths observed by ground-based wind profilers and an airborne lidar. J. Atmos. Oceanic Technol., 16, 584–590, doi: 10.1175/1520-0426(1999)016<0584:ACDOMO>2.0.CO;2.

Xiang, Y., Q. H. Ye, J. G. Liu, et al., 2016: Retrieval of planetary boundary layer height based on image edge detection. Chinese J. Lasers, 43, 0704003, doi: 10.3788/CJL201643.0704003. (in Chinese)

Xu, G. R., R. Ware, W. G. Zhang, et al., 2014: Effect of off-zenith observations on reducing the impact of precipitation on ground-based microwave radiometer measurement accuracy. Atmos. Res., 140–141, 85–94, doi: 10.1016/j.atmosres.2014.01.021.

Xu, G. R., B. K. Xi, W. G. Zhang, et al., 2015: Comparison of atmospheric profiles between microwave radiometer retrievals and radiosonde soundings. J. Geophys. Res. Atmos., 120, 10,313–10,323, doi: 10.1002/2015JD023438.

Yamada, T., 1976: On the similarity functions A, B and C of the planetary boundary layer. J. Appl. Meteor., 15, 781–793, doi: 10.1175/1520-0469(1976)033<0781:OSFAPB>2.0.CO;2.

Yang, F. Y., 2018: Comparison of determination methods and characteristics of boundary layer height in semi-arid area. Master dissertation, Lanzhou University, 80 pp. (in Chinese)

Yang, F. Y., N. Zhang, L. F. Zhu, et al., 2016: Comparison of the mixing layer height determination methods using lidar and microwave radiometer. Plateau Meteor., 35, 1102–1111, doi: 10.7522/j.issn.1000-0534.2015.00045. (in Chinese)
Yang, T., Z. F. Wang, W. Zhang, et al., 2017: Technical note: Boundary layer height determination from lidar for improving air pollution episode modeling: Development of new algorithm and evaluation. Atmos. Chem. Phys., 17, 6215–6225, doi: 10.5194/acp-17-6215-2017.

Yin, J., C. Y. Gao, J. Hong, et al., 2019: Surface meteorological conditions and boundary layer height variations during an air pollution episode in Nanjing, China. J. Geophys. Res. Atmos., 124, 3350–3364, doi: 10.1029/2018JD029848.

Zeman, O., 1979: Parameterization of the dynamics of stable boundary layers and nocturnal jets. J. Atmos. Sci., 36, 792–804, doi: 10.1175/1520-0469(1979)036<0792:POTDOS>2.0.CO;2.

Zeman, O., and H. Tennekes, 1977: Parameterization of the turbulent energy budget at the top of the daytime atmospheric boundary layer. J. Atmos. Sci., 34, 111–123, doi: 10.1175/1520-0469(1977)034<0111:potteb>2.0.co;2.

Zhang, A. C., C. G. Sun, and Y. Tian, 1990: The observing results of atmospheric mixed layer in Beijing district and the assessment of theoretical models. Acta Meteor. Sinica, 48, 345–354, doi: 10.11676/qxxb1990.042. (in Chinese)

Zhang, Q., and S. Wang, 2008: A study on atmospheric boundary layer structure on a clear day in the arid region in Northwest China. Acta Meteor. Sinica, 66, 599–608, doi: 10.11676/qxxb2008.057. (in Chinese)

Zhang, Q., J. Zhang, J. Qiao, et al., 2011: Relationship of atmospheric boundary layer depth with thermodynamic processes at the land surface in arid regions of China. Sci. China Earth Sci., 54, 1586–1594, doi: 10.1007/s11340-011-4207-0.

Zhang, X. Y., X. D. Xu, Y. H. Ding, et al., 2019: The impact of meteorological changes from 2013 to 2017 on PM$_{2.5}$ mass reduction in key regions in China. Sci. China Earth Sci., 62, 1885–1902, doi: 10.1007/s11340-019-9343-3.

Zhao, H. J., H. Z. Che, X. G. Xia, et al., 2019: Climatology of mixing layer height in China based on multi-year meteorological data from 2000 to 2013. Atmos. Environ., 213, 90–103, doi: 10.1016/j.atmosenv.2019.05.047.

Zhao, L., B. Han, S. H. Lyu, et al., 2018: The different influence of the residual layer on the development of the summer convective boundary layer in two deserts in Northwest China. Theor. Appl. Climatol., 131, 877–888, doi: 10.1007/s00704-016-1003-4.

Zhao, M., M. Q. Miao, and Y. C. Wang, 1991: Boundary-Layer Meteorology Course. China Meteorological Press, Beijing, 217–219. (in Chinese)

Zhong, J. T., X. Y. Zhang, Y. Q. Wang, et al., 2017: Relative contributions of boundary-layer meteorological factors to the explosive growth of PM$_{2.5}$ during the red-alert heavy pollution episodes in Beijing in December 2016. J. Meteor. Res., 31, 809–819, doi: 10.1007/s13351-017-7088-0.

Zhong, J. T., X. Y. Zhang, Y. S. Dong, et al., 2018: Feedback effects of boundary-layer meteorological factors on cumulative explosive growth of PM$_{2.5}$ during winter heavy pollution episodes in Beijing from 2013 to 2016. Atmos. Chem. Phys., 18, 247–258, doi: 10.5194/acp-18-247-2018.

Zilitinkevich, S., and D. V. Mironov, 1996: A multi-limit formulation for the equilibrium depth of a stably stratified boundary layer. Bound.-Layer Meteor., 81, 325–351, doi: 10.1007/bf02430334.

Zilitinkevich, S., and A. Baklanov, 2002: Calculation of the height of the stable boundary layer in practical applications. Bound.-Layer Meteor., 105, 389–409, doi: 10.1023/a:1020376832738.

Zilitinkevich, S., A. Baklanov, J. Rost, et al., 2002: Diagnostic and prognostic equations for the depth of the stably stratified Ekman boundary layer. Quart. J. Roy. Meteor. Soc., 128, 25–46, doi: 10.1256/00359000260498770.

Zilitinkevich, S., I. Esau, and A. Baklanov, 2007: Further comments on the equilibrium height of neutral and stable planetary boundary layers. Quart. J. Roy. Meteor. Soc., 133, 265–271, doi: 10.1002/qj.27.

Zou, J., J. N. Sun, A. J. Ding, et al., 2017: Observation-based estimation of aerosol-induced reduction of planetary boundary layer height. Adv. Atmos. Sci., 34, 1057–1068, doi: 10.1007/s00376-016-6259-8.