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Improved retrieval of cloud base heights from ceilometer using a non-standard instrument method

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ABSTRACT

Cloud-base height (CBH) is a basic cloud parameter but has not been measured accurately, especially under polluted conditions due to the interference of aerosol. Taking advantage of a comprehensive field experiment in northern China in which a variety of advanced cloud probing instruments were operated, different methods of detecting CBH are assessed. The Micro-Pulse Lidar (MPL) and the Vaisala ceilometer (CL51) provided two types of backscattered profiles. The latter has been employed widely as a standard means of measuring CBH using the manufacturer's operational algorithm to generate standard CBH products (CL51 MAN) whose quality is rigorously assessed here, in comparison with a research algorithm that we developed named value distribution equalization (VDE) algorithm. It was applied to both the profiles of lidar backscattering data from the two instruments. The VDE algorithm is found to produce more accurate estimates of CBH for both instruments and can cope with heavy aerosol loading conditions well. By contrast, CL51 MAN overestimates CBH by 400 m and misses many low level clouds under such conditions. These findings are important given that CL51 has been adopted operationally by many meteorological stations in China.

1. Introduction

Cloud base height (CBH) is one of the fundamental cloud variables (Hirsch et al., 2011) governing the surface radiation budget especially downward longwave radiation (Viúdez-Mora et al., 2015). It is a prerequisite to retrieve other cloud micro-physical properties (Martucci and O'Dowd, 2011; Garrett and Zhao, 2013). Many previous studies attempted to retrieve CBH from different satellite sensors (Forsythe et al., 2000; Hutchison, 2002; Hutchison et al., 2006; Meerkötter and Zinner, 2007; Sharma et al., 2016; Sun et al., 2016). All passive sensors aboard satellite are, however, inherently difficult to do so because the outgoing infrared radiance is much more sensitive to the IR emission from top of a cloud than its bottom (Kim et al., 2011), except for high-resolution sensors like VIIRS that may see cloud bases through their gaps (Zhu et al., 2014). Besides, the satellite CBH products often provide very few diurnal samples for any particular location (Martucci et al., 2010).

Ground-based active sensors can detect CBH much more readily and accurately (Goodman and Henderson-Sellers, 1988), at a high temporal resolution of much spatial coverage. Lidar and radar are two most useful sensors for observing cloud boundaries with complimentary merits due to their different spectral bands (Wang and Sassen, 2001; Garrett and Zhao, 2013). They have been employed to generate CBH climatology at the ARM South Great Plain (e.g. Dong et al., 2010; Xi et al., 2010) that can be used for evaluating cloud simulations by weather forecast model (e.g. Willén et al., 2005; Illingworth et al., 2012; Morcrette et al., 2012).

Lidar and cloud ceilometer have been much more widely employed than cloud radar for the determination of cloud bases and cloud occurrences (e.g., Clothiaux et al., 2000; Martucci et al., 2007; Zhao et al., 2012; Costa-Surós et al., 2013; Lee et al., 2017). Ceilometer, a low-energy lidar, has been used as an operational sensor at meteorological stations for providing continuous CBH data as a standard output product at a low cost during both day and night (Martucci et al., 2010;

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Román et al., 2017). Its backscattering information may also be used to infer aerosol layer structures and atmospheric boundary layer heights (e.g., Zéphoris et al., 2005; Martucci et al., 2007; Morille et al., 2007; Schween et al., 2014).

While the gross feature of CBH can be readily obtained by any active sensor, it is still a challenge to acquire precise estimation of CBH (Clothiaux et al., 2000). To detect clouds from lidar measurements, algorithms have to distinguish signal changes from aerosol, clouds, and random noise, especially under heavy polluted conditions like China and India (Li et al., 2016). Without heavy aerosol loading, clear cloudy scenes can be differentiated by setting thresholds of the backscatter signals (Pal et al., 1992; Clothiaux et al., 2000), except for very thin clouds in a hazy boundary layer which requires a more delicate algorithm to detect the CBH.

Given the wide usage of ceilometers in CBH detection, the accuracy of derived CBHs is thoroughly evaluated in this study and a more accurate method than the conventional one is developed in this study. The manufacturer operational CBH products from Vaisala ceilometer (CL51 MAN) is evaluated against other CBH products generated from a micropulse lidar (MPL) and from a ceilometer by Vaisala CL51 using our Value Distribution Equalization (VDE) algorithm (Zhao et al., 2014), along with the CBHs determined from radiosonde profiles of atmospheric humidity.

Section 2 describes the field experiments, instruments, datasets and methods used in the study. Analyses of the MPL and CL51 CBH products and improvement are elaborated in Section 3. Section 4 summarizes the study.

2. Data and methods

2.1. Field campaign

A field experiment named the Atmosphere-Aerosol-Boundary Layer-Cloud (A^2BC) Interaction Joint Experiment was carried out at the Xingtai meterological station (37.18°N, 114.37°E, 183 m above the mean sea level) from May 1 to December 31 in 2016, with an intensive observation period (IOP) from May 1 to June 15 in 2016. Only the measurements made during the IOP were examined in this study. The site of the experiment was at the eastern foot of Taihang Mountain, 18.5 km away from the small city of Xingtai and 96.1 km away from the big city of Shijiazhuang, where air pollution is among the worst in China. Fig. 1 is a map showing the city locations (marked as red dots) and the topography distribution around the field campaign site (marked as yellow dot).

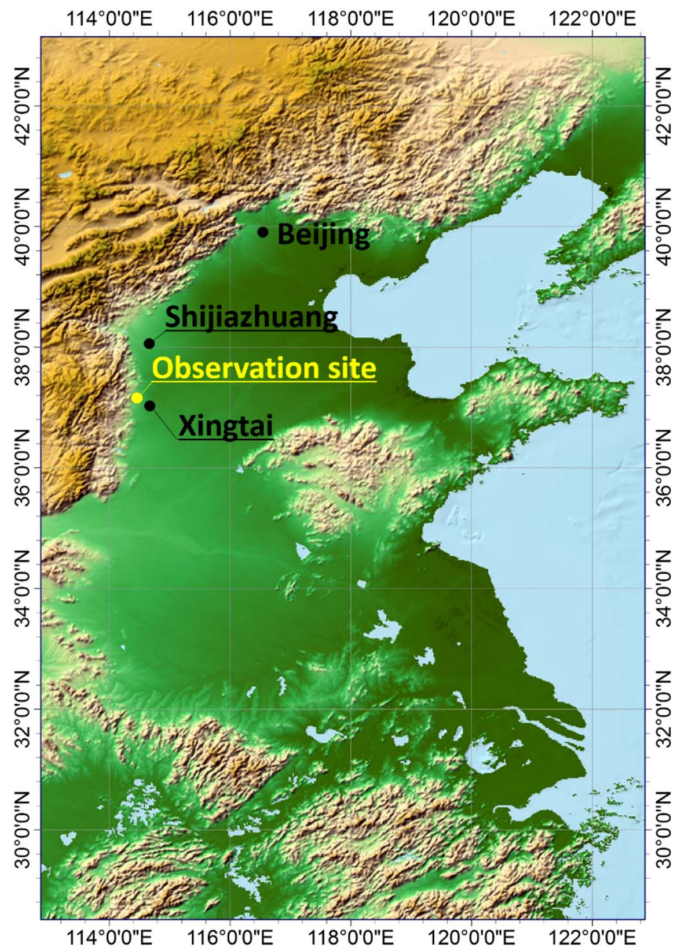

Fig. 1. The location of the field campaign (marked by yellow point) and the topography surrounded the observation site. Also marked are the three cities of Beijing, Shijiazhuang, and Xingtai in this region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Characteristics of the instruments used in this study during our field campaign at Xingtai site.

Instrument	Temporal/spatial resolution	Wavelength/ frequency	Observed or derived quantity
MPL	30 s/30 m	532 nm	Altitude of clouds
MMCR	60 s/15 m	35 GHz	Reflectivity factor, Doppler velocity, Doppler width
CL51	36 s/10 m	910 nm	Altitude of clouds
TSI	10 min/–	–	Cloud fraction
Radiosonde	1 s/–	–	Profiles of relative humidity, pressure and temperature

The mark "–" represents no value in the table.

2.2. Instruments

The data we used in this study are from the following instruments: (1) The Millimeter-wavelength Cloud Radar (MMCR), (2) the MPL, (3) the Vaisala CL51, (4) the Total Sky Imager (TSI), and (5) the Radiosonde. Table 1 shows the information about these instruments, which will also be described in detail below. Note that all these ground-based instruments were placed no more than 30 m from each other.

2.2.1. Micro pulse lidar (MPL)

The MPL is a ground-based lidar which can be used to determine the altitude of clouds overhead, with an eye-safe pulse energy at a wavelength of 532 nm from the Nd: YLF. In addition to the real-time detection of clouds, the subsequent processing of the lidar signal returns can also broaden their advantages to characterize the properties of aerosols, boundary layer structure as well as the evolution of pollutants in heavily particle-laden regions (Satheesh et al., 2006; Zhao et al., 2014). The MPL instrument used in this study is manufactured by the Sigma Space Corporation (Spinhirne, 1993; Mendoza and Flynn, 2006). It transmits laser pulses into the atmosphere and subsequently measures the intensity of backscattered light using photon-counting detectors and transforms the signal into atmospheric information. In this study, the backscattered light is processed as normalized relative backscatter (NRB) (Campbell et al., 2002) and is then adopted by our VDE algorithm for CBH detection (MPL VDE). The MPL observation time resolution is 30 s and the vertical spatial resolution is set as 30 m with a maximum detection altitude of 20 km.

2.2.2. Vaisala CL51

As a single-wavelength backscatter lidar, Vaisala CL51 is a laser ceilometer with the ability to determine the altitude of clouds automatically and continuously with the near infrared 910 nm to avoid