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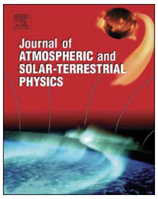

LIDAR and Millimeter-Wave Cloud RADAR (MWCR) techniques for joint observations of cirrus in Shouxian (32.56°N, 116.78°E), China

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ABSTRACT

Cirrus plays an important role in the regulation of the Earth-atmosphere radiation budget. The joint observation using both the LIght Detection And Ranging (LIDAR) and Millimeter-Wave Cloud RADAR (MWCR) was implemented in this study to obtain properties of cirrus at Atmospheric Radiation Measurement (ARM) mobile facility in Shouxian (32.56°N, 116.78°E, 21 m above sea level), China during May–December 2008. We chose the simultaneous measurements of LIDAR and MWCR with effective data days, and the days must with cirrus. Hence, the cirrus properties based on 37 days of data between October 18th and December 13th, 2008 were studied in the present work. By comparing the LIDAR data with the MWCR data, we analyzed the detection capabilities of both instruments quantitatively for measuring the cirrus. The LIDAR cannot penetrate through the thicker cirrus with optical depth (τ) of more than 1.5, while the MWCR cannot sense the clouds with an optical depth of less than 0.3. Statistical analysis showed that the mean cloud base height (CBH) and cloud thickness (CT) of cirrus were 6.5 ± 0.8 km and 2.1 ± 1.1 km, respectively. Furthermore, we investigated three existing inversion methods for deriving the ice water content (IWC) by using the separate LIDAR, MWCR, and the combination of both, respectively. Based on the comparative analysis, a novel joint method was provided to obtain more accurate IWC. In this joint method, cirrus was divided into three different categories according to the optical depth ($\tau \leq 0.3$, $\tau \geq 1.5$, and $0.3 < \tau < 1.5$). Based on the joint method used in this study, the mean IWC was calculated by means of the statistics, which showed that the mean IWC of cirrus was 0.011 ± 0.008 g m^{-3}.

1. Introduction

Cirrus is defined as a cloud which appears at high altitude (often above 5 km) and is composed of small ice crystals (Avery et al., 2012). Cirrus which covers the area of 30% above the Earth plays an important role in the regulation of the Earth-atmosphere radiation budget and has a significant impact on global water cycle (Donovan and Van Lammeren, 2001; Hogan et al., 2006; Shupe et al., 2008). Since cirrus reflects the solar radiation as well as absorbs the longwave radiation emitted from the Earth, the balance between these two opposite effects will affect the net radiation budget (Kienast-Sjögren et al., 2016). Although, cirrus is likely to act as a positive feedback on inter-annual climate fluctuations, by reducing the Earth's ability to radiate longwave radiation to space in response to planetary surface warming (Zhou et al., 2014). There are several uncertainties in the feedback of cirrus (Delanoë and Hogan, 2010; Kienast-Sjögren et al., 2016). Lack of adequate observations is one of the main reasons for the uncertainties of feedback evaluation because of the scarcity of observational data that affect the correct parameterization of cirrus at present (Alam et al., 2010). Both the occurrence height and the ice water content (IWC) of cirrus, bring difficulties to field observation and lead to the scarcity of observation data (Juan and Jietai, 2006).

Clouds and their associated microphysical processes strongly regulate radiative transfer and the hydrological cycle (Hogan et al., 2006; Shupe et al., 2008; Alam et al., 2014). They are often themselves important for end users of weather forecasts, who may

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be interested not in cloud cover, but in other variables determined by cloud properties, such as surface precipitation, temperatures, or shortwave/ultraviolet radiation. In order to provide these variables, accurate prediction of the vertical and horizontal distribution of cloud ice and liquid water contents is necessary (Illingworth et al., 2007). Remote sensing from space provides global cloud properties of cloud cover (Jakob, 2003), liquid water path (Greenwald et al., 1993), and even more information concerning the IWC has been derived from the microwave limb sounding instruments (Li et al., 2005). Satellite remotely sensed products have the drawback that information concerning cloud vertical structure is usually lacking (Seifert et al., 2007). The successful launch of a cloud radar on CloudSat (Stephens et al., 2002) accompanied by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO; Winker et al., 2009) provided valuable information. Delanoë and Hogan (2010) provided variational method combining the Radar, Lidar and Radiometer retrievals to study the properties of ice clouds. The ongoing Atmospheric Radiation Measurement (ARM) project (Stokes and Schwartz, 1994) bridges the gap between ground-based studies and satellite remote sensing by operating a network of ground stations to continuously monitor cloud-related variables over multiyear time periods.

LIght Detection And Ranging (LIDAR) is one of the common instruments used for cirrus observation (Comstock and Sassen, 2001). Xinlian et al. (2006) obtained the depolarization of cirrus by employing a polarized LIDAR at Hefei in China. Min et al. (2011) investigated the distribution of cirrus using data from the space-borne LIDAR (Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) aboard the CALIPSO). Their analysis showed that the horizontal distribution of multilayered cirrus cloud systems with different kinds of the cloud is closely associated with the latitudinal distribution of different kinds of cloud. Further, Ruijin et al. (2011) statistically analyzed the properties of cirrus in the semi-arid area of China. According to scattering theory, LIDAR is more sensitive to the bulk of smaller particles (ice crystals), which hold the majority in cirrus, due to the short wavelength of the laser source (Seifert et al., 2007; Shupe et al., 2008; Delanoë and Hogan, 2010). The sensitivity, however, is a double-edged sword. The higher sensitivity for the smaller ice crystals will result in the weaker penetration ability, so LIDAR cannot penetrate through the cirrus with large optical depth. Furthermore, it is not easy to retrieve microphysical properties of cirrus only using the LIDAR data and the combined method will be more effective.

Millimeter-Wave Cloud RADAR (MWCR) uses longer wavelength (at a wavelength of 3.16 mm) than the LIDAR as its source. Thus, it has weaker sensitivity for smaller ice crystals but can penetrate through the thicker cirrus. Accordingly, the joint observation by means of both the LIDAR and MWCR simultaneously (Delanoë and Hogan, 2010), has become the main trend of cirrus observation; since these two instruments respectively have their advantages and disadvantages which are complementary in their functions. Zhien and Sassen (2001) developed a cloud detection algorithm that can differentiate among various atmospheric targets using ground-based remote sensors. Additionally, Zhien and Sassen (2002a) also described a retrieval algorithm to estimate vertical profiles of IWC and general effective size from the combined LIDAR and RADAR measurements. They applied the combined LIDAR–RADAR algorithm to 1000 h of Raman LIDAR and MWCR data collected during the ARM program. Further, Mcgill et al. (2004) presented initial results of the combined airborne LIDAR-RADAR measurements during CRYSTAL-FACE. They presented the comparison of instruments sensitivity within the context of particular CRYSTAL-FACE observations. Also, Mcgill et al. (2004) reported that the optically thin cirrus was frequently missed by the RADAR, but was easily profiled with the LIDAR. In contrast, optically thick clouds and convective cores quickly extinguish the LIDAR signal but were easily probed with the RADAR. Borg et al. (2011) examined the sensitivity of MWCR to optically thin single layer cirrus. They characterized the sensitivity in terms of optical depth (τ) and infrared radiative flux using over three years of coincident Raman LIDAR and MWCR observations. Their results highlighted the importance of combining Raman LIDAR, or other sensitive cloud LIDARs that were able to measure cloud extinction directly, with the MWCR, in order to characterize the cloud radiative forcing for thin cirrus cases.

The present work employed both the LIDAR and MWCR for simultaneous cirrus observation at ARM mobile facility in Shouxian, China during October–December 2008. Based on the comparison between the LIDAR and MWCR data, the quantitative analysis for their detection capability is carried out. In order to overcome the limitations of the separate observations, we provided a novel inversion method to combine the data from both instruments for deriving the cirrus properties including the cloud base height (CBH), cloud thickness (CT), and IWC. The statistical results and corresponding analysis for these properties are also illustrated to characterize the cirrus over Shouxian, China.

2. Measurement and method

The ARM mobile facility was deployed at Shouxian (32.56°N, 116.78°E, 21 m above sea level) in China by the U.S. Department of Energy and a campaign lasting for about 7 months from May to December 2008 was implemented. The ARM mobile facility (http://www.arm.gov/data/datastreams) comprised of LIDAR (American SigmaSpace, USA), MWCR (American HoneyWell, USA) and other radiation instruments. The LIDAR has a wavelength of 532 nm, with the spatial and temporal resolutions of 15 m and 2 min, respectively. The minimum detection range of the LIDAR is 15 m. The characteristics of MWCR include the wavelength of 3.16 mm (around 95 GHz) at spatial and temporal resolutions of 43 m and 1 min, with the minimum and the maximum detection ranges of 155 m and 15 km, respectively. According to the data from ARM plan observed in Shouxian site, LIDAR detection data was available from May 14th to December 28th, 2008. While data from the MWCR was detected between October 15th and December 15th, 2008. The mutual data measured by both the LIDAR and MWCR are from October 15th to December 15th in 2008, a total of 62 days. During the above simultaneous data period, a total of 5 days (October 15th–17th and December 14th–15th) in which both the LIDAR and MWCR data are not complete. Hence, the simultaneously available data from October 18th to December 13th, a total of 57 days, has been utilized in the present study. In these 57 days of data, we have excluded the days with some data which is invalid as the cirrus is not detected above 5 km. In order to ensure that the statistical results and methods in the paper are more realistic and objective, we have removed the data missing and invalid data days. Finally, after removing the invalid data days, a total of complete and effective data was only available for 37 days. Regarding the spatial and temporal resolution differences between the LIDAR and MWCR, we first processed the both datasets to match each other for the effective comparison (Kunling et al., 2015). Both the final datasets have the coincident spatial and temporal resolutions of 43 m and 2 min, respectively with a minimum detecting range of 155 m.

3. Results and discussion

3.1. Limitations between LIDAR and MWCR

As a result of the relative longer wavelength, MWCR cannot