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A new retrieval method for the ice water content of cirrus using data from the CloudSat and CALIPSO

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ABSTRACT

The CloudSat and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) are the members of satellite observation system of A-train to achieve the quasi-synchronization observation on the same orbit. With the help of active (CALIOP and CPR) and passive payloads from these two satellites, respectively, unprecedented detailed information of microphysical properties of ice cloud can be retrieved. The ice water content (IWC) is regarded as one of the most important microphysical characteristics of cirrus for its prominent role in cloud radiative forcing. In this paper, we proposed a new joint (Combination) retrieval method using the full advantages of different well established retrieval methods, namely the LIDAR method (for the region Lidar-only), the MWCR method (for the region Radar-only), and Wang method (for the region Lidar-Radar) proposed by Wang et al. (2002). In retrieval of cirrus IWC, empirical formulas of the exponential type were used for both thinner cirrus (detected by Lidar-only), thicker cirrus (detected by radar-only), and the part of cirrus detected by both, respectively. In the present study, the comparison of various methods verified that our proposed new joint method is more comprehensive, rational and reliable. Further, the retrieval information of cirrus is complete and accurate for the region that Lidar cannot penetrate and Radar is insensitive. On the whole, the retrieval results of IWC showed certain differences retrieved from the joint method, Ca&Cl, and ICARE which can be interpreted from the different hypothesis of microphysical characteristics and parameters used in the retrieval method. In addition, our joint method only uses the extinction coefficient and the radar reflectivity factor to calculate the IWC, which is simpler and reduces to some extent the accumulative error. In future studies, we will not only compare the value of IWC but also explore the detailed macrophysical and microphysical characteristics of cirrus.

1. Introduction

Cloud not only has the ability to reflect its thermal radiation but also absorbing or scattering solar shortwave and terrestrial longwave radiations. They also regulate and effect radiant energy distribution of the Earth-atmosphere system, which has important implications for the global climate change (Harrison et al., 1990). The cloud with distribution, diversity and complexity, variance of height, phase distribution of inner particles of cloud, particle size, and number concentrations etc., causing different radiation impacts on the shortwave (ultraviolet and visible) and the longwave (infrared) spectral bands, which also play a different role in the Earth-atmosphere radiative transfer. For example, cirrus composed of ice-crystal particles in the upper troposphere have a smaller impact on incident radiation from the solar shortwave radiation, but can also absorb longwave radiation reflected back to space from the ground. Consequently, the cirrus mainly has a warming effect on the radiation budget in the Earth-atmosphere system and other types of cloud are opposite (Stephens, 2005). Owing to the limit of detection, the understanding of cloud optical and microphysical properties is incomplete; and the description of characteristic parameters of cloud in climate model development and research also not accurate and detailed. Consequently, this results in enormous uncertainty on the cloud radiation

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effect calculation and simulation (Treut et al., 2007). It is a basic and important aspect for global weather and climate research to realize deeply into the physical structure and distribution characteristics of the clouds in nature (Bu et al., 2016).

The observational means for measuring the properties of clouds include ground, aircraft, ship, and satellite which have been used in several international research programs (Peng et al., 2010; Bu et al., 2016). The satellite observation, currently, becomes one of the most important ways in the cloud studies because of its effective advantages containing wide coverage, high repetition rate, strong objective truth, and whole cloud parameters, together with reliable information sources (Dai et al., 2011). The CloudSat equipped with 94-GHz CPR (Cloud Profile Radar, W-band) is the first solar polar-orbiting satellite dedicated to observing clouds, which has the characteristic of high vertical resolution and can accomplish to probe three-dimensional structure of clouds in the global (Stephens et al., 2008). The satellite is located on solar synchronous orbit at a height of around 705 km, and satellite around the Earth with one complete circle is called a scan track. The whole time and length is about 99 min and 40022 km, respectively. Each rail has 36,383 sub-satellite pixel points, the beam coverage width whose along rail resolution is 2.5 km, cross rail resolution is 1.4 km, together with the vertical resolution of 240 m at each pixel of sub-satellite point (Yang et al., 2014; Stephens et al., 2008). The CloudSat not only focuses on detection of cloud layer consisted of big scale particles having a thicker optical thickness and internal information of cloud can be detected. It can generate a vertical profile from the content of liquid water and ice water in the cloud, but it is not detailed to probe thin clouds at the top, and the information of aerosol distribution is difficult to be presented.

CALIPSO equipped with CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization), is a dual wavelength sensitive Lidar that can not only provide cloud and aerosol characteristics changing with the Earth's latitude and longitude, but also provide the vertical distribution of cloud and aerosol data (Deng et al., 2013; Winker et al., 2009; Bu et al., 2016). It is very sensitive for thin and delicate cloud top, especially suitable for the study of cirrus. However, it is difficult to go through the thick clouds to observe the complete information of internal structure. Both CloudSat and CALIPSO are very similar, and their time difference is only 12.5 s. Consequently, the two instruments complement each other. The advantages of detection are obvious, and hence, two active observation instruments achieve quasi-synchronous observation for the same cloud under the condition of the approximate period with same horizontal resolution. This can produce their advantages and make the acquired data more accurately which reflects the vertical and temporal profiles of cloud physical properties (Deng et al., 2010; Sato and Okamoto, 2011). Although, each instrument individually can be used to retrieve clouds properties, its own advantages, and disadvantages. For instance, the Radar alone cannot accurately estimate particle size and is less sensitive to small particles. On the other hand, the Lidar is more sensitive to optically thin clouds but suffers from attenuation (Bu et al., 2016).

Currently, the cloud research mainly focuses on two aspects, which are the analyses of macroscopic and microscopic physical properties of clouds using satellite data retrieved from the CloudSat and CALIPSO. Sassen et al. (2008) examined the distribution of cirrus using the results detected by the CloudSat and CALIPSO. They found that the global average incidence of cirrus was about 16.7% and focused primarily on the regularity of distribution of cirrus. Grenier et al. (2009) studied the distribution of cloud and aerosol parameters in the thin ice cloud over Polar Regions by analyzing the data measured by the CloudSat and CALIPSO which involved the interaction of aerosols, clouds, and radiation; and further contributed to understanding the climate change in Polar Regions. Delanoë and Hogan (2008) developed an algorithm on the optical hypothesis to retrieve the property of ice cloud using data observed from ground-based radar by applying the algorithm to improve data measured by the CloudSat and CALIPSO satellite sensors (Delanoë and Hogan, 2010). Stein et al. (2011) compared different retrieval algorithms to study properties of an ice cloud from the CloudSat, CALIPSO, and MODIS instruments. They explained that the difference of retrieval results was caused by different microphysical assumptions, and emphasized what is necessary to define unified microphysical assumptions in all retrieval algorithms. Later, Deng et al. (2013) compared microphysical properties of an ice cloud retrieved by some A-Train satellites and obtained the results of practical detection and analyzed what reasons could cause the difference in the derived results. This is associated with factors such as input parameters given in the inversion algorithm, and assumption of the shape and size of the particles etc.

Peng et al. (2013) divided the East Asia into 5 sub-regions by analyzing the data from the CloudSat satellite which further refined the vertical distribution of cloud over this region. Further, Ye et al. (2014) analyzed the characteristics of the vertical structure of clouds in Western China and the surrounding areas, by using the joint data product of cloud classification observed from the CloudSat and CALIPSO satellites during March 2007–February 2008. The results showed that the occurrence frequency of cloud top and base height have obvious regional and seasonal characteristics over different heights, and the seasonal variation of cloud top height was significantly higher than the cloud base height. Huo (2015) also analyzed the properties of cloud distribution over the North China, the Japan Sea, and the Pacific Ocean regions using the cloud data product detected by the CloudSat and CALIPSO satellites from January 2007 to December 2010. The statistical results revealed that the content of ice particles in the cirrus accounted for an absolute majority, and the proportion of liquid and ice particles were quite equal to each other. In a recent study by Bu et al. (2016) proposed an inversion algorithm to retrieve cirrus ice water content (IWC) using data observed by ground-based radar and depending on the optical thickness as the threshold over Shouxian, China. They reported that the combination algorithm proposed by them was in agreement with that of other algorithms mentioned in their work, which is more effective and comprehensive. Added to this, Das et al. (2016) used the combined CloudSat-CALIPSO data products for the summer season (June–August) of 2006–2010 to present the statistics of cloud macrophysical and microphysical properties. The statistical results derived from their study showed that the IWC and ice water path over India were maxima compared to the other monsoon regions. Overall, the research progress in recent years is based on the CloudSat and CALIPSO satellite data which mainly retrieved the statistics of the vertical structure and microphysical characteristics of cloud. What's more in the study of inversion algorithm to derive the cloud characteristics from the spaceborne radar data. There are so many assumptions of combining multiple instruments to retrieve the cloud characteristics since the accumulative error are relatively large which will affect the accuracy of the inversion results to some extent (Delanoë and Hogan, 2010).

In this paper, we proposed a new joint (Combination) method combining the data obtained from LIDAR and millimeter-wave cloud Radar (MWCR) and making full use of their own advantages for the retrieval of IWC characteristics of cirrus, which is introduced in detail and thoroughly in the later sections. The structure of this paper is as follows: Firstly, introduces various retrieval algorithms of IWC of cirrus in Section 2. Later, we have presented typical examples of cirrus and innovative point-joint algorithm as proposed in this paper. Further, we moved to write discussion and assessment of the results-IWC of cirrus obtained by various retrieval algorithms in Section 3. Finally, the main conclusions with a brief summary are given in Section 4.

2. Materials and methods

Here, we first introduce the IWC of cirrus obtained by six different retrieval methods. We discussed below thoroughly the retrieval results derived from different methods.

2.1. Empirical formulas

The Combination method we put forward which is based on the three