Atmospheric Research 199 (2018) 54–61

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Tropical echo-top height for precipitating clouds observed by multiple active instruments aboard satellites

Yilun Chen, Yunfei Fu*

School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China

ARTICLE INFO

Keywords:
Echo-top height
PR
CPR
CALIOP
Radiative forcing

ABSTRACT

The echo-top height observed by the Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) has been used by some studies as an approximate calculation of the precipitating-cloud-top height to simulate radiative forcing or to identify overshooting convection. However, due to the low sensitivity (~17 dBZ) of PR, the PR-echo-top height is lower than the actual precipitating-cloud-top height. Here, the echo-top heights of the tropical precipitating cloud detected by PR, the Cloud Profiling Radar (CPR), and the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) were investigated to evaluate the underestimation of the PR-echo-top height to the actual precipitating-cloud-top height. The results show that there were significant spatial variations in the underestimates of precipitating-cloud-top height by PR. The model simulation showed that these underestimates led to an underestimation of the radiative forcing of the Earth system, the relative error of which was ~10% with 1-km underestimation and ~20% to 80% with 7-km underestimation when the cloud optical thickness was fixed to 10. Therefore, the underestimates of precipitating-cloud-top height by PR should be taken into consideration when using PR-echo-top height.

1. Introduction

The echo-top height observed by the Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) reflects the "precipitation-top height", which is commonly used to estimate rain rate or assess the magnitude of convection development (Hamada et al. 2015; Shige and Kummerow 2016). In some studies, the PR-echo-top and PR-echo-bottom heights have been subtracted to calculate the thickness of the anvil (Schumacher and Houze 2006; Li and Schumacher 2011; Yang et al. 2015). The PR-echo-top height, assumed to approximate the cloud-top height, has been compared with the tropopause to identify overshooting (tropopause-penetrating) convection (Liu and Zipser 2005; Xian and Fu 2015). Furthermore, the PR-echo-top height has been taken as an input parameter in some models to simulate the heating profile or radiative forcing (Lau and Wu 2010; Yang et al. 2017). It also has been used to identify precipitation type (deep weak convective precipitation, shallow precipitation, and deep strong convective precipitation) over the Tibetan Plateau (Fu et al. 2016).

However, due to the low sensitivity (~17 dBZ) of the PR (Schumacher and Houze 2003), its echo-top height is lower than the actual precipitating-cloud-top height, which can lead to the miscalculation of the anvil, the overshooting convection, and the radiative forcing. Based on the assumption that the infrared brightness temperature represents the cloud-top height, Lau and Wu (2011) compared the PR-echo-top height with the infrared brightness temperature observed by the TRMM Visible and Infrared Scanner (VIRS). They found that heavy rain was associated with the cold infrared brightness temperature and elevated PR-echo-top heights, and light rain was associated with the warm infrared brightness temperature and low PR-echo-top heights, respectively, whereas intermediate rain (25th to 75th percentile) contributed to a wide range of infrared brightness temperature and PR-echo-top heights. Recently, Chen and Fu (2017) concluded that the beam-filling problem also resulted in a difference (~5 to 15 K) in the infrared brightness temperature within each warm-rain-PR pixel. These studies indicate that the infrared brightness temperature of VIRS does not fully represent the actual cloud-top height.

Therefore, the accurate assessment of actual cloud-top height relies on active sensors with high sensitivity, such as, LIDAR or Cloud Profiling Radar (CPR). Casey et al. (2007) investigated the cloud-top difference between the TRMM PR and Geoscience Laser Altimeter System (GLAS) using coincident scans (1279 pixels in total), finding that the echo-top height peaked at 5 km for PR and 15–16 km for GLAS. Li and Schumacher (2011) compared a coincident scan of PR and CloudSat CPR, concluding that PR underestimated the anvil tops from 1 to 10 km with an average of 5 km, and some of the anvil samples were missed by PR. However, these studies lacked a sufficient number of

---

* Corresponding author.
E-mail address: fyf@ustc.edu.cn (Y. Fu).

http://dx.doi.org/10.1016/j.atmosres.2017.08.008
Received 22 May 2017; Received in revised form 4 August 2017; Accepted 8 August 2017

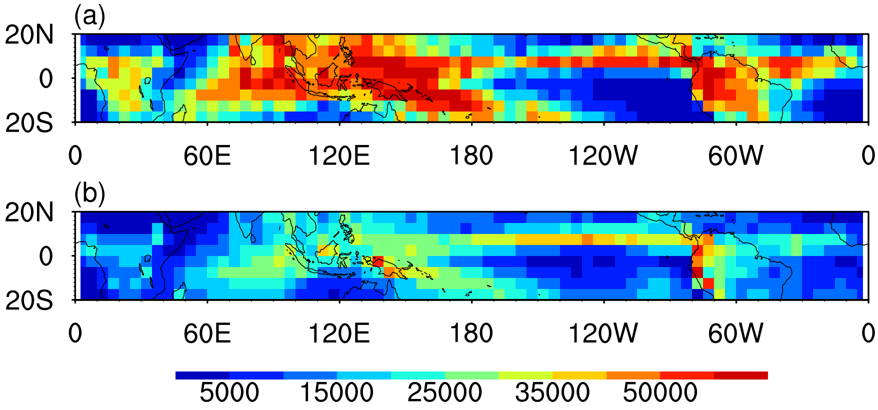

Fig. 1. Distributions of the total number of sample for precipitating cloud observed by (a) PR, (b) CPR from 13th June 2006 to 31st December 2010. Please note that PR observations were only used for time periods from 0100 to 0200 and 1300 to 1400 local time since CPR observes at approximately 1330 and 0130 LST.

samples and therefore it is difficult to assess the regional differences.

The cloud-top height of the precipitating cloud has an important effect on cloud morphology, particle size, radiative forcing, and liquid water content (Rangno and Hobbs 2005). Understanding the difference between the PR-echo-top height and the actual precipitating-cloud-top height will provide an accurate input for model simulation to effectively reduce the error in estimating these physical parameters. Although some studies have measured the echo-top height of the CloudSat CPR or TRMM PR alone (Riley and Mapes 2009; Fu et al. 2012; Chen et al. 2016; Chen et al. 2017), due to the lack of a uniform standard (CPR was generally used to study the "cloud" rather than the "precipitating cloud", and PR was generally used to study the "precipitation") or lack of sufficient samples (Casey et al. 2007; Li and Schumacher 2011), the tropics-wide difference between PR-echo-top height and actual precipitating-cloud-top height is not yet understood. In this study, TRMM PR reflectivity and CloudSat/CALIPSO L2 data were used to compare the echo-top height difference of the tropical precipitating clouds and evaluate the impact of underestimating the cloud-top height on radiative forcing estimates.

2. Data and method

The PR operates at 13.8 GHz with 5-km horizontal and 250-m vertical resolution after a 2001 boost (Kummerow et al. 1998). As members of the A-Train constellation, CloudSat and CALIPSO were launched in 2006 using a sun-synchronous 705-km-altitude orbit with 1330 and 0130 LST (Local Standard Time) crossings of the equator. The CPR onboard CloudSat operates at 94 GHz with 240-m vertical resolution and − 30-dBZ sensitivity, which can observe 2D (cross-track and vertical) cloud structure (Stephens et al. 2008). The minimum detectable reflectivity was also reported as − 28 dBZ in some publications (Im et al. 2005). The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard CALIPSO is a near-nadir viewing two-wavelength polarization-sensitive LIDAR that can more effectively detect thin clouds, compared with CPR or other passive remote sensors, to accurately obtain cloud-top height. For example, Liu et al. (2016) found that CPR missed 24–36% oceanic thin warm clouds (optical thickness < 4) after comparing with CALIOP. The CALIOP provides 532 and 1064 nm attenuated backscatter profiles at the horizontal resolution of 1 km (333 m) and the vertical resolution of 60 m (30 m) at altitudes of 8.3 to 20.2 km (− 0.5 to 8.3 km) (Winker et al. 2009).

We used PR 2A25 V7 data to provide reflectivity and 3D rain rate (Iguchi et al. 2000). A precipitating cloud was defined by a near-surface rain rate > 0.1 mm/h and a maximum reflectivity not < 17 dBZ. The PR-echo-top height was defined as the first layer from top to ground with a minimum echo exceeding 17 dBZ.

The standard product 2B-GEOPROF provides CPR reflectivity and a cloud mask. The "cloud mask" contains values between 0 and 40, and increasing values indicate a reduced probability of a false detection (Marchand et al. 2008). The 2B-CLDCLASS product provides a "precipitation flag" for each pixel using temperature and reflectivity thresholds, including "no precipitation", "liquid precipitation", "solid precipitation", and "possible drizzle" (Sassen and Wang 2007). Precipitating cloud observed by CPR was defined by pixels with a precipitation flag of "liquid precipitation" or "solid precipitation". The highest layer with reflectivity greater than − 30 dBZ and a cloud mask not < 20 was defined as the CPR-echo-top height.

The 2B-GEOPROF-LIDAR is a collaborative product of CPR and CALIOP, which integrates CALIOP pixels to CPR pixels and provides the LIDAR cloud fraction within a CPR footprint (Mace and Zhang 2014). The CALIOP-echo-top height was defined as the highest layer with a cloud fraction > 50%. Because of the sensitivity and strong attenuation of CALIOP, the precipitating flag identified by CPR was integrated with CALIOP. In general, the CALIOP-echo-top and CPR-echo-top heights represent the actual cloud-top height. Only certain high thin cirrus and shallow continental stratus will be below the detection threshold of the CPR, and CALIOP can identify them correctly.

To reduce the influence of interannual variability on the results, we chose to study the period during which PR, CPR, and CALIOP were all working normally (13th June 2006 to 31st December 2010). Because CPR and CALIOP always observe at approximately 1330 and 0130 LST, we only counted the PR pixels from 0100 to 0200 LST, and 1300 to 1400 LST, to avoid the error caused by the diurnal variation of the precipitating cloud. Based on the above restrictions, the number of precipitating cloud samples observed by the PR and CPR showed similar patterns (Fig. 1), and the number of samples in the 5 × 5° grid was sufficient for statistical analysis. Overall, CPR and PR both observed more precipitating cloud samples over the Central Africa, Indonesia, Argentina, central Indian Ocean, and Intertropical Convergence Zone, whereas the less samples occurred in southeast and northeast Pacific, and African coast. Some discrepancies occurred in part of the south Atlantic, and east Pacific near the South America, where the precipitating cloud samples observed by CPR were even greater than the PR precipitating cloud samples. Please note that time matching between PR and CPR (near-coincident PR-CPR-CALIOP dataset) was not used in this part and later statistical analysis because of the rare near-coincident samples.

SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer) was used to estimate the effect of cloud-top-height underestimation on radiative forcing using the tropical standard atmospheric profile (Ricchiazzi et al. 1998). This model is scripted in the FORTRAN 77 language and designed for the analysis of radiative transfer problems in satellite remote sensing (Fu 2014) and atmospheric energy budget (Fu et al. 2017). The SBDART utilizes the file named INPUT to handle the user inputs. Users can define tens of interesting parameters and output options including atmospheric profiles, aerosols, surfaces and clouds. If the parameters are not specified by the users in INPUT file, these parameters will be determined as default settings. Because the