Atmospheric Research 169 (2016) 113–126

Contents lists available at ScienceDirect

Atmospheric Research

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

Seasonal Variability of Storm Top Altitudes in the Tropics and Subtropics Observed by TRMM PR

Fengjiao Chen [a], Yunfei Fu [a,b,c,*], Peng Liu [a,d], Yuanjian Yang [a,c]

[a] School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui 230026, PR China
[b] State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, 100081, PR China
[c] Key Laboratory of Atmospheric Sciences and Satellite Remote Sensing of Anhui Province, Anhui Institute of Meteorological Sciences, Hefei, Anhui 230031, PR China
[d] Anhui Academy for Environmental Science Research, Hefei, Anhui 230071, PR China

ARTICLE INFO

Article history:
Received 10 April 2015
Received in revised form 17 August 2015
Accepted 17 September 2015
Available online 30 September 2015

Keywords:
convective
stratiform
storm top altitude
vertical profile
rain rate

ABSTRACT

Seasonal variability of storm top altitudes for convective and stratiform precipitation in the tropics and subtropics are investigated based on measurements of the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) from 1998 to 2011. Statistically, the spatial distribution of mean convective storm top altitudes shows a large variation between land and ocean, while the stratiform storm tops exhibit insignificant land-ocean differences. Seasonal variances of tropical convective and stratiform storm top altitudes are small, with their means are approximately at 5 km (6 km) and 5.5 km (6 km) over the ocean (land) in each season. In the subtropics, the difference of the storm top altitudes between summer and winter reaches ~4 km and ~2 km for convective and stratiform precipitation, respectively. The zonal mean storm top altitudes of stratiform precipitation are highly correlated with the zonal averaged air temperature and sea surface temperature. Additionally, the mean storm tops of higher altitudes correspond with larger mean rain rates for both convective and stratiform precipitation at the seasonal scale. Such relationship satisfies the quadratic functions with a correlation coefficient of 0.9. On the basis of this relationship, the summer mean rain rates are retrieved from storm top altitudes, which are 1-3 mm/h and 0.3-0.9 mm/h smaller than the observed ones, for convective and stratiform precipitation, respectively. These results suggest that the quadratic function between storm top altitudes and rain rates have potential applications in precipitation parameterization of models and climatic studies.

1. Introduction

The storm top altitude is referred to as the maximum height of particles in the top of precipitating clouds detected by precipitation radar inside precipitating cloud, which is related to updraft strength and the atmospheric stability (Houze et al., 1993; Liu, 2007). Usually, the storm top altitude is related to the wavelength of precipitation radar, the longer the wavelength of precipitation radar is, the lower the storm top altitude it detects. Due to TRMM (Tropical Rainfall Measuring Mission) PR (Precipitation Radar) operates at the Ku band (2.17 cm wavelength) with a sensitivity of ~17 dBZ (decrease to 18dBZ, after the boost in August 2001), it is a better effective measurement to detect storm top altitude than below. On the other hand, the higher altitude of the storm top, which always corresponds to the stronger updrafts inside the thicker clouds with larger particles in the top of clouds, often generates the heavier precipitation (Barrett, 1970; Arkin and Ardanuy, 1989). When storm top altitudes inside convective precipitating clouds extend to the tropopause (Alcala and Dessler, 2002), they play an important role in the transition of air from the troposphere to stratosphere, which will affect stratospheric chemistry and troposphere-surface radiative balance (Forster and Shine, 1999). Studies have shown that the storm top altitudes are closely related to precipitation type (Churchill and Houze, 1984; Hong et al., 1999; Kummerow et al., 2001; Olson et al., 2001), rainfall intensity (Short and Nakamura, 2000) and lightning flash rate (Futyan and Del Genio, 2007). To know the temporal and spatial variation of the storm top altitudes will be helpful in evaluating the performance of the numerical models, such as global circulation models (GCMs). Usually, GCMs are evaluated by comparing their output cloud, precipitation, temperature, etc., with results observed by instruments on the ground or onboard satellites (Palutikof et al., 1997; Ricardo and Palutikof, 2001; Zhang et al., 2005). Unfortunately, few studies have been carried out to compare GCMs' storm top altitudes with those of observations.

Ground-based precipitation radar is an effective instrument to characterize storm top altitudes. However, observations from its limited locations and coverage are unable to evaluate the storm top altitudes in the tropics and subtropics. The launch of the TRMM PR provides us a unique opportunity to comprehensively characterize the storm top altitudes for convective and stratiform precipitation, because TRMM PR products supply three-dimensional rainfall structures for both

* Corresponding author at: School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui 230026, PR China.
E-mail address: fyf@ustc.edu.cn (Y. Fu).

http://dx.doi.org/10.1016/j.atmosres.2015.09.017
0169-8095/

precipitation types (Kummerow et al., 1998). Till now, the TRMM PR products have been applied to uncover characteristics of the storm top altitudes. Short and Nakamura (2000) pointed out that the storm top altitudes have a distinct bimodal distribution over the ocean, with the lower mode near 2 km and the upper mode at ~5 km. Setvák et al. (2003, 2012) explored the deep convective storm top altitudes on the basis of multi-satellite observations. Liu et al. (2007, 2012) also investigated the characteristics of deep and overshooting convective precipitation during summer and winter and found the most intense convection mainly occurs over land. Fu et al. (2005, 2006) found the difference of the altitudes between storm top and cloud top decreases as surface rain rate increases in a convective system in the southeastern mainland of China during summer based on the measurements from TRMM PR and VIRS (Visible and Infrared Scanner). A similar phenomenon has been shown by Cao (2010) who confirmed that departures between storm top altitudes and cloud top altitudes for convective precipitation are smaller than that for stratiform precipitation, and the departures are smaller at larger rain rates on the basis of the joint observations from PR and CPR (Cloud Profile Radar) in Asia. Fu et al. (2012) revealed the climatological distributions of storm top altitudes in summer over Asia based on PR measurements from 1998 to 2007. Results indicate 70% of convective storm top altitudes vary from 8 km to 12 km, and 5 km to 8 km for stratiform precipitation. Moreover, it is found that the mean altitudes of both convective and stratiform storm tops in summer over Asia increase with increasing mean surface rain rate, which fits the curve of a quadratic function. Consequently, it will be useful to obtain the relationship between storm top altitudes and surface rain rates, so that storm top altitude maybe used as a proxy for surface rain rate and as another method of parameterization of precipitation in GCMs.

Although the previous studies extended the understanding of the storm top altitudes, the knowledge on the seasonal variability of storm top altitudes and the quantitative assessment of their relationships with rain rate in the tropics and subtropics is limited. The objectives of this study are as follows: 1) to reveal the seasonal variability of storm top altitudes for convective and stratiform precipitation in the tropics and subtropics, 2) to investigate the relationship between the mean storm top altitude and the mean rain rate, and 3) to test an algorithm of rain rate retrieval from storm top altitude at the seasonal scale utilizing TRMM PR measurements between 1998 and 2011.

2. Data and Methods

The dataset of TRMM PR 2A25 version 7 (hereafter referred to as PR 2A25) from 1998 to 2011, provided by GSFC/NASA (Goddard Space Flight Center, National Aeronautics and Space Administration), covering the tropics and subtropics (35^{o}S~35^{o}N) is used in this study. Precipitation information, including location in longitude and latitude, near surface rain rate and three-dimensional radar reflectivity, are given in each PR profile (Iguchi and Meneghini, 1994; Iguchi et al., 2000). In PR 2A25, precipitation profiles are classified into three categories: stratiform, convective and "others" on the basis of the vertical pattern of the profiles (i.e., V method; Awaka et al., 1997, 2009) and on the horizontal variability of the radar echo (i.e., H method; Steiner et al., 1995). Briefly, a rain profile is classified as stratiform if the PR detects a bright band near the freezing level. If no bright band exists and any value of radar reflectivity in the beam exceeds a predetermined value of 39 dBZ (the threshold for identifying convective), the profile is classified as convective. The convective category includes a sub-category of shallow convective precipitation, referred to as precipitating clouds occurring in a relatively lower part of the atmosphere where collision-coalescence (warm-rain process) is the only method of hydrometeor growth (Schumacher and Houze, 2003a). The PR has a sensitivity of ~17dBZ, which corresponds to ~0.4 mm/h in rain rate (Schumacher and Houze, 2003b), pixels with near surface rain rates smaller than 0.4 mm/h are ignored.

Because there are some uncertainties in the rain profiling algorithm for the TRMM PR (Iguchi et al., 2009), the original radar reflectivity profile from PR 2A25 data are used to calculate the storm top altitudes in this work. Different methods have been used to define storm top altitude observed by PR in previous studies. Alcala and Dessler (2002) require the profile contain a top layer with a thickness of at least 6 range gates (~1.5 km) where all the reflectivity exceeds a minimum threshold of 12dBZ. Liu et al. (2007) take the first layer from top to ground with a minimum radar echo exceeding 20dBZ as the storm top altitude. Sensitivity tests show that there is no substantial difference of the seasonal storm top altitude for these two methods. And taking sensitivity of PR into consideration, in this paper we will follow the second method as the criteria of storm top altitude for seasonal studies. Additionally, storm top altitudes in this work are relative to the mean sea level. Therefore, precipitating clouds with different thicknesses over plateau and over plain can share the same storm top altitude.

In this study, we will focus on climatological characteristics of storm top altitudes for convective and stratiform precipitation at the seasonal scale. Seasons are divided according to the northern hemisphere seasons, i.e., spring (March, April, May—MAM), summer (June, July, August—JJA), autumn (September, October, November—SON), and winter (December, January, February—DJF).

3. Results

3.1. Horizontal patterns of storm top altitudes

Firstly, it is necessary to get the general concept of the sample distributions for both convective and stratiform precipitation measured by PR in JJA and DJF from 1998 to 2011 before taken statistics. Fig. 1 shows the distributions of these samples. It is clear that many samples are presented in each 0.5^o longitude-latitude grid box during 1998~2011, therefore results based on 0.5^o resolution are statistically reliable (Fu et al., 2008). It is obvious that the occurrence of stratiform precipitation is more prevalent than that of convective precipitation for both winter and summer.

The horizontal distributions of multi-season mean storm top altitudes for both convective and stratiform precipitation at 0.5^o resolution are shown in Fig. 2. In total, mean storm top altitudes for convective precipitation vary from 3-7 km over the ocean and 5-10 km over the land, whereas values are more uniform (4-9 km) for stratiform precipitation over the land and the ocean. It is clear that storm top altitudes for convective precipitation show remarkable land-sea discrepancy, as revealed by Nesbitt et al. (2006), which is probably attributed to the surface heating and topography (Stanley and Carlson, 1986). The strongest convective precipitating clouds are found over the Tibet Plateau, the Andes and the Africa Plateau (Zipser et al., 2006); once convection occurs, storm top altitudes will exceed 9 km at the seasonal scale. However, for stratiform precipitation, the effect of surface heating and topography is not that obvious, and only a slight increase of storm top altitude is found over the land. These findings not only suggest that storm top altitudes for convective precipitation are generally higher than that for stratiform precipitation, but also indicate that storm top altitudes for both convective and stratiform precipitation over land are higher than that over ocean.

It is also worth noting that storm top altitudes for both convective and stratiform precipitation in regions, i.e., the East Pacific and the southern Indian Ocean, are much lower (even below 3 km), and the area fractions are not small, especially for convective precipitation. It is revealed by previous studies that these are sufficient low clouds, i.e., cumulus, stratocumulus, stratus and shallow convective clouds in these regions (Hartmann and Short, 1980; Schumacher and Houze, 2003a; Liu and Fu, 2009; Liu and Zipser, 2009). Further examination of storm top altitude for shallow convective precipitation will also be presented in this section.