Radiative forcing of the tropical thick anvil evaluated by combining TRMM with atmospheric radiative transfer model

Yuanjian Yang,1,2 Yunfei Fu,1,2* Fang Qin1 and Jiachen Zhu1
1School of Earth and Space Sciences, University of Science and Technology of China, Hefei, PR China
2Key Laboratory of Atmospheric Sciences and Satellite Remote Sensing of Anhui Province, Anhui Institute of Meteorological Sciences, Hefei, PR China

*Correspondence to: Y. Fu, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China.
E-mail: fyf@ustc.edu.cn

Abstract

The presences of anvil clouds significantly affect the tropical mean radiation budget and increase the uncertainty of climate model simulations. In this study, the climatological mean distributions of thick anvil parameters, such as top, bottom, occurrence, cloud effective radius (CER) and cloud optical depth (COD) in the tropics (20°S–20°N) are investigated by Tropical Rainfall Measuring Mission’s (TRMM) precipitation radar (PR) and visible and infrared scanner (VIRS) from 1998 to 2007. The thick anvil radiative forcing at shortwave (0.2–4 μm) and longwave (4–50 μm) length, i.e. Shortwave radiative forcing (SRF) and Longwave radiative forcing (LRF) and their net effects at different altitudes are simulated with Santa Barbara DISORT Atmospheric Radiative Transfer Model (SBDART). The results show that thick anvils present higher top/bottom, smaller CER, and thicker COD over land than those over ocean. At the top of atmosphere (TOA), net radiative effects of thick anvils are positive warming, which means the earth-atmosphere system obtains energy forced by thick anvils. At Earth surface, net radiative effects of thick anvils are positive warming at land surface and negative cooling at ocean surface, respectively. In general, anvil SRF, LRF and net effects vary with different geographical locations and also present large land–ocean differences in the tropics, due to different anvil properties forced by the surface heating and topography. All spatial patterns of stronger anvil SRF, LRF and net effects are well matched with the places where exist higher fractions of anvils, such as Asian monsoon zone, the Intertropical Convergence Zone (ITCZ), the South Pacific Convergence Zone (SPCZ), tropical Africa, Mid-America and South America. In addition, the present work provides an evidence that it is an effective approach to calculate quantitatively the grid-cell SRF and LRF of cloud at a large scale by using the SBDART model with inputs from satellite observations.

Keywords: radiative forcing; anvil; TRMM; SBDART

1. Introduction

It has been estimated that clouds cover more than 50% of the globe (Liou, 2002), which are very important in regulating atmospheric radiative transfer via their greenhouse versus albedo effects (Stephens and Webster, 1981; Stephens, 2005; Waliser et al., 2009; Zhang et al., 2013; Hong and Liu, 2015). As a typical non-precipitating cloud, thick anvil closely associated with deep convection is one of the most important cloud types in the tropics. Previous studies pointed out that the presences and longevity of anvil clouds may have a significant impact on the tropical circulation through significantly affecting the tropical mean radiation budget, which can increase the uncertainty of climate model simulations (Webster and Stephens, 1980; Machado and Rossow, 1993; Yao and Del Genio, 1999; Colman, 2003; Clement and Soden, 2005).

Using a single- or multi-satellite observation, therefore, many previous studies have revealed the geographical distributions of anvil occurrence, three-dimensional structures (e.g. top/bottom/thick) of anvil clouds (Schumacher and Houze, 2006; Cetrone and Houze, 2009; Fu et al., 2010; Yuan and Houze, 2010; Li and Schumacher, 2011; Yuan et al., 2011; Young et al., 2012) and their corresponding spectral characteristics (e.g. visible/infrared radiance) (Machado and Rossow, 1993; Fu et al., 2010; Young et al., 2013; Yang et al., 2015) in a regional or tropics-wide scale. For example, high occurrences of thick anvils located most frequently over Asia monsoon region, equatorial Africa, the Maritime Continent, and Panama (Cetrone and Houze, 2009; Yuan and Houze, 2010; Li and Schumacher, 2011). Especially, based on observation of precipitation radar (PR) aboard on the Tropical Rainfall Measuring Mission (TRMM) satellite, Li and Schumacher (2011) found that thick anvils have an average 17-dBZ echo top of ~8.5 km and an average thickness of ~2.7 km in the tropics, which were usually higher and thicker over land compared to ocean. Recently, by using the advantage in near synchronization observation of merged PR and VIRS, Yang et al. (2015) further explored that visible/infrared reflectance and the equivalent brightness temperature of a
blackbody at different wavelengths for thick anvils in the tropical-wide regions, and their spectral signals implied that thick anvil cloud presents thinner optical depth and their cloud tops consists many more smaller-ice droplets over land than those over ocean. In contrast, the radiative forcings of thick anvils were provided by few studies, which only focused on their general radiative characteristics of tropical anvil (Webster and Stephens, 1980; Ackerman et al., 1988; Machado and Rossow, 1993). However, the geographical distribution of radiative forcing climatology of thick anvil is limited in their ability to measure anvils vertical structure and their spectral signals and microphysical properties at the same time with a radiative transfer model simulation, leaving large gaps in our comprehensive understanding of radiative characteristics of thick anvils.

For this purpose, in this study, PR and VIRS onboard TRMM are firstly used to capture thick anvil occurrence, top/bottom, and their spectral signals during 1998–2007, following Yang et al. (2015). Moreover, cloud effective radius (CER) and cloud optical depth (COD) of thick anvils are retrieved by the bispectral reflectance (BSR) algorithm (Nakajima and Nakajma, 1995; Fu, 2014), using the visible and infrared reflectance of VIRS with Santa Barbara DISORT Atmospheric Radiative Transfer Model (SBDART) (Ricchiazzi et al., 1998). Finally, the thick anvil radiative forcings at shortwave (0.2–4 μm) and longwave (4–50 μm) lengths, i.e. Shortwave radiative forcing (SRF) and Longwave radiative forcing (LRF), and their net effects at the top of atmosphere (TOA)/earth surface are simulated by SBDART with input of anvil occurrence, geometrical (top and bottom) and microphysical parameters (CER and COD).

2. Data and methods

The launch of the TRMM presents an unique opportunity to comprehensively understand the precipitation types and three-dimensional rainfall structures with their corresponding spectral signals (Iguchi et al., 2000; Fu et al., 2003; Kodama and Tamaoki, 2002; Awaka et al., 2009; Liu and Fu, 2010; Yang et al., 2015; Fu et al., 2017). TRMM PR 2A25 and VIRS 1B01 (hereafter referred to as 2A25 and 1B01) datasets from 1998 to 2007, provided by Goddard Space Flight Center, will be used in this study. A merged dataset at PR spatial resolution was established by collocating 2A25 and 1B01 products with a weight-averaged method, which picks the mean value of VIRS at PR pixels (Yang et al., 2015).

In the 2A25, original radar reflectivity profile is used to identify rain classifications and their tops (Awaka et al., 1998, 2009; Iguchi et al., 2009; Chen et al., 2016). The thick anvils are defined as echo with a rain type: equal to 160 – ‘Maybe stratiform, but rain hardly expected near surface. Bright band may exist but is not detected’; 170 – ‘Maybe stratiform, but rain hardly expected near surface. Bright band hardly expected. Maybe cloud only’; or 300 – ‘Other’. In addition, anvil reflectivity must be greater than 17 dBZ and have an echo base higher than 3 km (Li and Schumacher, 2011; Yang et al., 2015). The errors for the retrieval of bottom and top mainly depend on the detection sensitivity of PR. Here, only single-layer thick anvils, whose vertical profiles present sequential reflectivities of $>$17 dBZ, are considered to calculate their radiative forcings. Anvil thickness is defined as the difference between the top and base. The reflectance at 0.63 and 1.6 μm from 1B01 products (hereafter referred to as RFI and RF2, respectively) are used to retrieve cloud parameters (CER and COD) using the BSR method (Fu, 2014), whose the retrieval errors for CER/COD is less than 10% for most cases of realistic clouds under realistic conditions (Nakajima and Nakajma, 1995).

Because of the large pixel samples from orbital-level data (2A25 and 1B01), probability density distribution, which is defined as the ratio of the samples at each anvil property (top/CER/COD) interval to the sum samples of all intervals for each anvil property, is used herein to reveal detailed differences of anvil property over different underline surfaces. In addition, the orbital data are grouped into $0.5^\circ \times 0.5^\circ$ grid boxes in which total observations, anvil samples, top/bottom and their vertical profiles with spectral signals over the global Tropics domain ($20^\circ S–20^\circ N$). The occurrence frequency (i.e. fraction) of thick anvil is defined as the ratio of the number of identified anvil pixels to the total number of observation pixels within each $0.5^\circ$ grid.

The SBDART model is intended for the calculation of radiative transfer problems covering a wide spectral range. It runs with 33 altitude layers and 4 radiation streams. Users can define about 60 initial parameters and 12 output options including cloud properties, aerosol characteristics and surface types, according to the research purpose. Cloud radiative forcing (CRF) is defined as the net radiation flux under all sky minus that under clear sky at TOA, surface and any other height. In this study, climatic mean anvil parameters (anvil top, bottom and fraction, CER and COD) are input to SBDART for calculating anvil SRF, LRF, and their net effects (i.e. SRF plus LRF) at surface and TOA in each $0.5^\circ$ grid, while other input parameters come from the tropical climatic mean database in SBDART.

3. Results

3.1. Vertical structure of thick anvil

Anvil geometric and physical parameters (e.g. top, bottom, thick, CER and COD) and fractions, as key input parameters to SBDART, played key roles in determining the process of thick anvil radiative forcing. The Contoured Frequency by Altitude Diagram (CFAD) is an effective method to analyze the characteristics of vertical structure of thick anvil, as suggested by previous studies (Yuter and Houze, 1995; Fu et al., 2003; Qin and Fu, 2016). The distribution can reflect the thick
anvil characteristics with different echo reflectivities and heights. The vertical structure of thick anvil over land and ocean is, respectively, extracted as shown in Figures 1(a) and (b), which presents a uniform shape over both land and ocean. Differently, the maximum frequency appears at approximately 6~9 km over land, while approximately 5~8 km over ocean. Moreover, the peak height over land is higher than that over ocean, and the maximum reflectivity (24 dBZ) mainly corresponds to a height of 6 km over land, which is also higher than that over ocean (~5.5 km). Furthermore, the Bi-parameter probability density distribution pattern of thick anvils in two-dimensional space consisting of anvil top height (ATH) and CER/COD over land and ocean (Figures 1(d)(f)). Over land, ATH of 5~10.5 km is mainly concentrated between 8 and 22 μm for CER, whereas ATH of 4.5~9 km is mainly concentrated between 10 and 25 μm for CER over ocean. Similarly, over land, ATH of 5~10.5 km is mainly concentrated between 40 and 110 for COD, whereas ATH of 4.5~9 km is mainly concentrated between 35 and 110 for COD. In general, as expected, thick anvils are usually higher/thicker over land than over ocean by 0.5~1 km, and also anvil physical parameters (e.g., CER and COD) are intimately tied to its geometric parameters (e.g., top and height).

3.2. Spatial distributions of anvil parameters

To reveal the differences in geographical distribution of anvil, Figure 2 shows spatial distributions of climatologies for the above parameters over global tropical areas during 1998~2007. In general, all these parameters present clear land–ocean differences. In detail, anvil tops/bottoms are higher over land (8.5~10 km/5.5~6.5 km) than those over ocean (7~8.5 km/4.5~5.5 km) (Figures 2(a) and (b)). Previous studies showed that convection were usually higher and thicker over land compared with ocean, which is probably attributed to the surface heating and topography (Stanley and Carlson, 1986; Nesbitt et al., 2006; Chen et al., 2016). Because anvil properties were closely tied to the properties of the parent convection, it can imply that the land-forcing effect can make anvils higher and thicker.

Moreover, smaller CER/thicker COD mostly occurred over land (16~19 μm/85~110 μm), while not over ocean (19~22 μm/60~95 μm) (Figures 2(c) and (d)), which suggests that anvil tops consist many more smaller-ice droplets and thicker vertical layers over land than those over ocean, due to land-forcing effects. Finally, higher fractions of anvils mainly appear over the Asian Monsoon Region, the Intertropical Convergence Zone (ITCZ), the South Pacific Convergence Zone (SPCZ), regions between the South America and the North America, and the Tropical Africa, where fractions vary between 0.4 and 0.6% (Figure 2(f)). While over most other areas, anvil fractions are less than 0.3%. Based on these, therefore, it should be checked that whether regional differences in tropical thick anvil parameters can modulate different earth-atmosphere energy budgets at surface and TOA.

3.3. Radiative forcing of thick anvil

CRF and its net radiative effect are key factors to evaluate the energy balance modulated by clouds. Figure 3 shows that geographical distributions of climatological mean SRF and LRF of thick anvil and their net radiative effect at TOA, respectively. At TOA, thick anvils induce weakly positive SRF over land, ranging from 0.05 to 0.15 W m⁻², while negative SRF over ocean, ranging from ~1.8 to ~0.2 W m⁻² (Figure 3(a)). It means that thick anvils mainly induce very weak shortwave heating and shortwave cooling at TOA over land and ocean, respectively. The weakly positive SRFs of thick anvils at the TOA over land are probably ascribed to the enhanced absorption effects of ice or water droplets in thick anvils. As well known, ice and water droplets will absorb certain radiation at near-infrared wavebands, meanwhile thick anvils over land contain many more smaller-ice or water droplets than those over ocean (Yang et al., 2015; also seen in Figure 2(c)), which is probably related to the enhancement of shortwave radiation absorption effect over land. Moreover, compare to low-albedo ocean surface, land surface represents higher albedo that will cause much more shortwave radiation reabsorbed by thick anvils through multiple reflections. Over land, therefore, there will be less outgoing shortwave radiation in the condition of the existence of thick anvils than that in clear-sky condition, which presents weakly positive SRF at TOA. As it should be, many more experimental observations combined with model simulations are needed to validate the above supposition regarding the weakly positive SRF at TOA caused by thick anvils over land.

Differently, thick anvil-induced LRF are positive heating over both land and ocean, where the values of LRFs are 0.4~4 W m⁻² (Figure 3(b)). Further, net radiative effect of thick anvil at TOA is positive warming over both land and ocean (Figure 3(c)), which means the earth-atmosphere system obtains energy forced by thick anvils, ranging from 0.2 to 5 W m⁻². In addition, the larger shortwave/longwave heating or cooling values at TOA mainly locate over the Asian Monsoon Region, ITCZ, SPCZ and the Tropical Africa, all of these regions present higher fractions of anvils (Figure 2(f)).

Similarly, Figure 4 shows that geographical distributions of climatological mean SRF and LRF of thick anvils and their net radiative effect at surface, respectively. At earth surface, anvil SRFs are negative cooling in both land and ocean, ranging from ~2 to ~0.05 W m⁻² (Figure 4(a)), while LRFs are positive heating in both land and ocean, varying between 0 and 1.2 W m⁻² (Figure 3(b)). While those at earth surface are positive warming over land and negative cooling over ocean, respectively. In contrast, SRFs at TOA (positive heating) are opposite with those.
Figure 1. Contoured Frequency by Altitude Diagram (CFAD) of radar reflectivity factor for thick anvil over land (a) and ocean (b). The Bi-parameter probability density distribution of anvils in two-dimensional space consisting of anvil top height and CER/COD over land (c)/(e) and ocean (d)/(f) during 1998–2007.
4. Conclusion and discussion

By merged observations of TRMM PR and VIRS from 1998 to 2007 with the BSR method, climatological mean anvil parameters are investigated, such as top, bottom, CER, COD and fractions. Thick anvil-induced SRFs, LRFs and net radiative effects are further simulated by SBDART with the inputs of anvil parameters. The conclusions can be summarized as follows. Firstly, thick anvils present higher tops/bottoms, smaller CER, and thicker COD over land than those over ocean. Higher fraction of anvil appears mainly Asian monsoon zone, ITCZ, SPCZ, tropical Africa, Mid-America and South America. Secondly, at TOA, anvil SRFs are positive warming over land, while those are negative cooling over ocean. Anvil LRFs are positive heating over both land and ocean. Correspondingly, net radiative effects of thick anvils are positive warming at TOA, which

at surface (negative cooling) over land, while SRFs at both TOA and surface are positive with similar heating values over ocean (Figures 3(a) and 4(a)). LRFs at TOA are stronger than those at surface by more than two times (Figures 3(b) and 4(b)), and both of which present obvious longwave heating. Therefore, thick anvil-induced net radiative effects at earth surface are positive warming (0.04~0.3 W m\(^{-2}\)) over land and negative cooling (~1~0.1 W m\(^{-2}\)) over ocean, respectively. It means that the land surface temperature is increased by 0.02~0.5 K, while the sea surface temperature is decreased by 0.05~0.5 K, according to the equation on the relationship between radiative forcing changes and global surface temperature changes (Dickinson, 1982; Cess et al., 1993). In addition, the regions of larger SRFs/LRFs at surface are also well matched with those of higher fractions of anvils.
means the earth-atmosphere system obtains energy forced by thick anvils. Thirdly, at earth surface, anvil SRFs (LRFs) are negative cooling (positive heating) over both land and ocean. Accordingly, net radiative effects of thick anvils are positive warming at land surface and negative cooling at ocean surface, respectively. Finally, anvil SRF, LRF and their net effects vary with different geographical locations in the tropics, and also exist significant land–ocean differences, due to different anvil properties forced by the surface heating and topography. All spatial patterns of anvil SRF, LRF and net effects are well matched with those of anvil fractions.

This paper focuses mainly on geographical distribution of radiative forcing climatology for thick anvil using the approach for quantitatively calculating the grid-cell radiative forcing at a large scale based on SBDART model with TRMM observations. Taking thick anvil as an example, generally, the present work may prove useful in improving our understanding of

Figure 3. The 0.5° grid-averaged distribution of anvil (a) SRF, (b) LRF and (c) their net effects (SRF + LRF) at TOA in the tropics from 1998 to 2007.

Figure 4. Same as Figure 3, but at earth surface.
cloud climate effects in the earth-atmosphere system. However, because the detection of thinner cloud by PR is limited to its long wavelength (2.2 cm), thinner anvils are usually missed. Nevertheless, such thin anvils can be effectively detected by Cloud Profiling Radar (CPR) onboard CloudSat (Yuan et al., 2011; Young et al., 2013). In addition, it is not considered in our present work that the effects of overlapping or multi-layer clouds on anvil radiative forcing (Zhang and Jing, 2010; Zhang et al., 2013). Therefore, more detailed research on all the anvils and their radiative forcings are still undergoing, using the combinations of TRMM and CloudSat observations in the horizontal and vertical directions.

Acknowledgements

We thank the anonymous reviewers for their useful comments and suggestions. This work is supported by the NSFC (grants 41230419, 91337213 and 41675041), the Special Funds for Public Welfare of China (grant GYHY201306077), and Open Meteorological Research Fund of Huaihe River Basin (HRM201507).

References

Ackerman TP, Liou K-N, Valero FPJ, Pfister L. 1988. Heating rates in tropical anvils. Journal of the Atmospheric Sciences 45: 1606–1623.
Awaka J, Iguchi T, Okamoto K. 1998. Early results on rain type classification by the Tropical Rainfall Measuring Mission (TRMM) precipitation radar. In Proceedings of the 8th USRI Commission F Open Symposium, Aveiro, Portugal, 143–146.
Awaka J, Iguchi T, Okamoto K. 2009. TRMM PR standard algorithm 2A23 and its performance on bright band detection. Journal of the Meteorological Society of Japan 87A: 31–52.
Cess RD, Zhang M-H, Potter GL, Barker HW, Colman RA, Dazlich DA, Del Genio AD, Esch M, Fraser JR, Galin V, Gates WL, Hack JJ, Ingram WJ, Kiehl JT, Lacis AA, Le Treut H, Li Z-X, Liang X-Z, Mahfouf J-F, McAvaney BJ, Melesko VP, Morcrette JJ, Randall DA, Roeckner E, Royer JF, Sokolov AP, Sporyshev PV, Taylor KE, Wang W-C, Wetherald RT. 1993. Uncertainties in CO₂ radiative forcing in atmospheric general circulation models. Science 262, 1252–1255.
Cetrone J, Houze RA. 2009. Anvil clouds of tropical mesoscale convective systems in monsoon regions. Quarterly Journal of the Royal Meteorological Society 135: 305–317, doi: 10.1002/qj.389.
Chen F, Fu Y, Liu P, Yang Y. 2016. Seasonal variability of rain top altitudes in the tropics and subtropics observed by TRMM PR. Atmospheric Research 169: 113–126, doi: 10.1016/j.atmosres.2015.09.017.
Clement AC, Soden B. 2005. The sensitivity of the tropical-mean radiation budget. Journal of Climate 18: 3189–3203.
Colman R. 2003. A comparison of climate feedbacks in general circulation models. Climate Dynamics 20: 865–873.
Dickinson RE. 1982. In Carbon Dioxide Review, Clark WC (ed). Clarendon: New York, NY: 101–133.
Fu Y. 2014. Cloud parameters retrieved by the bispectral reflectance algorithm and associated applications. Journal of Meteorological Research 28(5): 965–982.
Fu Y, Lin Y, Liu G, Wang Q. 2003. Seasonal characteristics of precipitation in 1998 over East Asia as derived from TRMM PR. Advances in Atmospheric Sciences 20: 511–529.
Fu Y, Peng S, Liu P, Cao A, Liu X, Li R, Liu Q, Wang Y. 2010. The anvil in summer Asia as detected by the TRMM PR. Acta Meteorologica Sinica (in Chinese) 68: 195–206.
Fu Y, Pan X, Yang Y, Chen F, Liu P. 2017. Climatological characteristics of summer precipitation over East Asia measured by TRMM PR: a review. Journal of Meteorological Research 31(1): 142–159, doi: 10.1007/s13351-017-6156-9.
Hong YL, Liu GS. 2015. The characteristics of ice cloud properties derived from CloudSat and CALIPSO measurements. Journal of Climate 28(9): 3880–3901, doi: 10.1175/JCLI-D-14-00666.1.
Iguchi T, Kozu T, Meneghini R, Awaka J, Okamoto K. 2000. Rain-profiling algorithm for the TRMM precipitation radar. Journal of Applied Meteorology 39: 2038–2052.
Iguchi T, Kozu T, Kwasniewski S, Meneghini R, Awaka J, Okamoto K. 2009. Uncertainties in the rain profiling algorithm for the TRMM Precipitation Radar. Journal of the Meteorological Society of Japan 87A: 1–30.
Kodama YM, Tamaoki A. 2002. A re-examination of precipitation activity in the tropics and the mid-latitudes based on satellite-derived data. Journal of the Meteorological Society of Japan 80: 1261–1278.
Li W, Schumacher C. 2011. Thick anvils as viewed by the TRMM precipitation radar. Journal of Climate 24(6): 1718–1735.
Liu KN. 2002. An Introduction to Atmospheric Radiation, 2nd ed. Academic Press: San Diego, CA; 583 pp.
Liu Q, Fu Y. 2010. Comparison of radiative signals between precipitating and non-precipitating clouds in frontal and typhoon domains over East Asia. Atmospheric Research 96: 436–446.
Machado LAT, Rossow WB. 1993. Structural characteristics and radiative properties of tropical cloud clusters. Monthly Weather Review 121: 3234–3260.
Nakajima TY, Nakajima T. 1995. Wide-area determination of cloud microphysical properties from NOAA AVHRR measurements for FIRE and ASTEX regions. Journal of the Atmospheric Sciences 52: 4043–4059.
Nesbitt SW, Cifelli R, Rutledge SA. 2006. Storm morphology and rainfall characteristics of TRMM precipitation features. Monthly Weather Review 134: 2702–2721.
Qin F, Fu Y. 2016. TRMM-observed summer warm rain over the tropical and subtropical Pacific Ocean: characteristics and regional differences. Journal of Meteorological Research 30(3): 371–385.
Ricchiazzi P, Yang SR, Gautier C, Sowle D. 1998. SBDART: a research and teaching software tool for plane-parallel radiative transfer in the Earth’s atmosphere. Bulletin of the American Meteorological Society 79(10): 2101–2114.
Schumacher C, Houze RA. 2006. Stratiform precipitation production over sub-Saharan Africa and the tropical East Atlantic as observed by TRMM. Quarterly Journal of the Royal Meteorological Society 132: 2235–2255.
Stanley GB, Carlson TN. 1986. Some effects of surface heating and topography on the regional severe storm environment. Part I: three-dimensional simulations. Monthly Weather Review 114: 307–329.
Stephens GL. 2005. Cloud feedbacks in the climate system: a critical review. Journal of Climate 18: 237–273.
Stephens G, Webster PJ. 1981. Clouds and climate: sensitivity of simple systems. Journal of the Atmospheric Sciences 38: 235–247.
Waliser DE, Li JL, Woods CP, Austin RT, Bacmeister J, Chern J, Del Genio A, Jiang JH, Kuang Z-M, Meng H, Minnis P, Platnick S, Rossow WB, Stephens GL, Sun-Mack S, Tao W-K, Tompkins AM, Vane DG, Walker C, Wu D. 2009. Cloud ice: a climate model challenge with signs and expectations of progress. Journal of Geophysical Research 114: D00A22.
Webster PJ, Stephens GL. 1980. Tropical upper tropospheric extended clouds: inferences from WRF. Monthly Weather Review 108(1): 2101–2114.
Webster PJ, Stephens GL. 2010. Clouds and climate: sensitivity of simple systems. Journal of the Atmospheric Sciences 38: 235–247.
Yuan J, Houze RA Jr. 2010. Global variability of mesoscale convective system anvil structure from A-Train satellite data. *Journal of Climate* **23**: 5864–5888.

Yuan J, Houze RA, Heymsfield AJ. 2011. Vertical structures of anvil clouds of tropical mesoscale convective systems observed by CloudSat. *Journal of the Atmospheric Sciences* **68**(8): 1653–1674.

Yuter SE, Houze RA Jr. 1995. Three dimensional kinematic and microphysical evolution of Florida cumulonimbus. Part II: frequency distributions of vertical velocity, reflectivity, and differential reflectivity. *Monthly Weather Review* **123**: 1941–1963.

Zhang H, Jing XW. 2010. Effect of cloud overlap assumptions in climate models on modeled earth-atmosphere radiative fields. *Chinese Journal of Atmospheric Sciences* **34**(3): 520–532 (in Chinese).

Zhang H, Peng J, Jing XW, Li JN. 2013. The features of cloud overlapping in eastern Asia and their effect on cloud radiative forcing. *Science China: Earth Sciences* **56**(5): 737–747.