ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 30, NO. 1, 2013, 142–152

An Investigation into the Relationship between Surface Rain Rate and Rain Depth over Southeast Asia

HU Liang*[1,2] (胡 亮), LI Yaodong[2,3] (李耀东), and DENG Difei[2] (邓涤菲)

[1]*National Satellite Meteorological Center, China Meteorological Administration, Beijing* 100081

[2]*Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

[3]*Beijing Aviation Meteorological Institute, Beijing* 100085

(Received 15 May 2012; revised 3 July 2012)

ABSTRACT

The relationship between surface rain rate and depth of rain system (rain depth) over Southeast Asia is examined using 10-yr Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) measurements. Results show that, in general, a large surface rain rate is associated with a deep precipitating system, but a deep rain system may not always correspond with a large surface rain rate. This feature has a regional characteristic. Convective rain develops more frequently over land than over the ocean, while stratiform rain can extend to higher altitudes over the ocean than over land. A light surface rain rate has the largest probability to occur, regardless of rain depth. A convective rain system is more likely associated with a stronger surface rain rate than a stratiform rain system. Results show that precipitation systems involve complex microphysical processes. Rain depth is just one characteristic of precipitation. A linear relationship between surface rain rate and rain depth does not exist. Both deep convective and stratiform rain systems have reflectivity profiles that can be divided into three sections. The main difference in their profiles is at higher levels, from 4.5 km up to 19 km. For shallow stratiform rain systems, a two-section reflectivity profile mainly exists, while for convective systems a three-section profile is more common.

Key words: TRMM, rain depth, convective rain, stratiform rain

Citation: Hu, L., Y. D. Li, and D. F. Deng, 2013: An investigation into the relationship between surface rain rate and rain depth over Southeast Asia. *Adv. Atmos. Sci.*, **30**(1), 142–152, doi: 10.1007/s00376-012-2097-5.

1. Introduction

Distribution, including the vertical spread of precipitation, is a basic variable required to describe water circulation on Earth. Much effort has been made to obtain reliable climatological data on precipitation. As an important parameter of the rain system, its depth can reflect many thermodynamic and dynamic characteristics of the atmosphere. Hu et al. (2010a) studied the spatial distribution and seasonal variation of rain depth over Southeast Asia using 10-yr data from Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) measurements, and found that the spatial distribution of rain depth and rain rate are closely correlated. Rain depths between convective and stratiform systems are distinctly different. A deeper convective rain system normally has a higher surface rain rate than a shallower stratiform system. Convective rain depth is affected by both dynamic and thermal processes, whereas stratiform rain depth is mainly impacted by thermal processes. There is a significant seasonal change in rain depth, which is consistent with the seasonal change of the climate system (Hu et al., 2010a). Using the echo-top height (having a similar meaning to rain depth, defined in this paper) of rain observed by TRMM-PR, Kodama and Tamaoki (2002) suggested that both deep stratiform and convective precipitation contribute to the strong precipitation along the subtropical mid-latitude precipitation zone in summer, while shallow stratiform and convec-

*Corresponding author: HU Liang, huliang314@gmail.com

tive precipitation largely contribute to the precipitation of the subtropical mid-latitude precipitation zone in fall and winter. Hu et al. (2010b) studied diurnal variations in rain depth over the Tibetan Plateau, and revealed that the rain depth there demonstrates different diurnal variation over different areas. The diurnal phase of rain depth lags the surface rain rate by about two hours. Fu et al. (2003) compared continental and oceanic rainfall over the tropics and subtropics of Southeast Asia using 1998 TRMM data, and found that an increase in cloud top is closely associated with surface rain rate. Fu (2006) also investigated the relationship between storm top (the echo-top of rain observed by TRMM-PR), cloud top, and surface rain rate during a rainfall event inside the subtropical high, and showed that the larger the surface rain rate is, the higher and more consistent both the cloud top and storm top are. These results are different from other studies using ground-based radar (e.g. Xu, 1992; Du and Gao, 1998; Li and Luo, 2006) in which rain echo depth was found not to be closely associated with surface rain rate due to the complicated microphysical processes of precipitation systems.

To further understand the relationship between rain depth and surface rain rate over different regions, 10-yr data from TRMM-PR measurements were used to study the relationships between surface rain rate and rain depth for convective and stratiform rainfall systems. The data and methodology are briefly discussed in section 2. The mean characteristics between surface rain rate and rain depth over different regions in Southeast Asia are examined in section 3. The probability distributions of rain depth and rain rate are discussed in section 4. A case study is presented in section 5. A comparison study of mean rain profiles is reported in section 6. A discussion and conclusions are presented in section 7.

2. Datasets and methodology

TRMM was set up specifically for the study of tropical rainfall, and it is good at observing low-latitude precipitation both over marine and continental areas (Kummerow et al., 2000). TRMM only scans a narrow track with a width of about 220 km. With the help of TRMM, a lot of meaningful studies have been carried out by domestic scholars (Fu and Liu, 2001; Fu et al., 2006; Liu and Fu, 2007; Fu et al., 2008). The period of observation data should be long enough in order to study the climatic characteristics of precipitation in different areas. In this paper, 10-yr TRMM 2A25 products (version 6) from 1998 to 2007 were used to clarify the characteristics between convective and stratiform systems (Awaka et al., 1998). Other types of precipitation are also included in the 2A25 data of TRMM precipitation, and different rain types have different dynamic, thermodynamic, and cloud microphysical structures (e.g., Liu and Takeda, 1989; Zipser and Lutz, 1994). Because precipitation types other than convective and stratiform rain cover a very small proportion of total precipitation (about 1% or less of the amount of rainfall and about 5.8% in terms of rain area; Fu and Liu, 2003; Fu et al., 2003), only convective and stratiform rain are considered when using TRMM precipitation to deal with the spatial distribution (Fu and Liu, 2003; Liu et al., 2007), seasonal variation (Yang and Smith, 2008; Liu and Zipser, 2009; Hu et al., 2010a) and diurnal cycle (Hu et al., 2010a; Yang et al., 2008) of precipitation and other variables, both domestically and internationally. Similarly, we did not consider other types of precipitation in this paper.

The depth of a rain system is derived from the difference between surface and top range bins of the TRMM PR 2A25 dataset (Hu et al., 2010a, b). The surface range bin corresponds to land surface altitude whereas the top range bin corresponds to the highest rain layer of TRMM-PR valid measurements. Thus, the rain depth in this paper is the echo depth of the rain pixel observed by TRMM-PR, and can be expressed by

$$H = H_{\rm t} - H_{\rm sfc} \ , \qquad (1)$$

where H represents rain depth while $H_{\rm t}$ and $H_{\rm sfc}$ represent top range bin and surface range bin observed by TRMM-PR respectively. A large value of H denotes a deep rain system and a small value of H means a shallow rain system. It should be noted that the rain depth (H) defined here is not the depth of the cloud system; a larger rain depth may correspond to a thinner cloud system, especially for stratiform rain events. The surface rain rate (R) used in this study is the rainfall estimate at the true (detected) surface bin in TRMM 2A25, which is calculated based on the $Z-R$ relationship

$$R = aZ^b \ , \qquad (2)$$

where Z represents the attenuation corrected reflectivity factor of TRMM-PR; and a and b are two parameters determined from the rain type and the height relative to the freezing level, the non-uniformity parameter, and the correction factor for the surface reference technique. As we can see, the rain depth is not a factor in the TRMM surface rain rate retrieval process, so the relationship between rain depth and surface rain rate studied in this paper is not due to the algorithm. The data used in this study are 10-yr (1998–2007) TRMM 2A25 convective and stratiform rain.

The surface rain rate (R) is categorized into nine categories when we study the mean rain depth associated with different rain rates:

R1: $R \leqslant 1$ mm h^{-1};

R2–R5: $n-1$ mm h$^{-1} < R \leqslant n$ mm h^{-1}, when n=2, 3, 4, 5;

R6: 5 mm h$^{-1} < R \leqslant 10$ mm h^{-1};

R7: 10 mm h$^{-1} < R \leqslant 20$ mm h^{-1};

R8: 20 mm h$^{-1} < R \leqslant 40$ mm h^{-1};

R9: 40 mm h$^{-1} < R$.

Such partitions are set up for enough samplings in each category. Meanwhile, rain depth (H) is correspondingly categorized into 15 types when we study the mean rain rate associated with different rain depth:

D1: $H \leqslant 1$ km;

D2–D14: $n-1$ km $< H \leqslant n$ km, when n=2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14;

D15: 14 km $< H$.

3. Mean characteristics between surface rain rate and rain depth over Southeast Asia

Figure 1 shows mean convective and stratiform rain depths varying with surface rain rate over different 10° (lon.) ×5° (lat.) boxes of Southeast Asia based on 10-yr TRMM data. In general, convective and stratiform rain depths both increase with increasing surface rain rate. The slope of convective rain is larger than that of stratiform rain. The same surface rain rate may associate with different rain depths in different regions. Over Northwest China and the Tibetan Plateau, convective rain depth is generally larger than stratiform rain depth. Meanwhile, over oceanic regions, including the Northwest Pacific, South China Sea and Indian Ocean, stratiform rain depth is generally larger than convective rain depth. In coastal and central areas of southern China and over Indo-China Peninsula and Indian Peninsulas, stratiform rain depth is larger than convective rain depth for light rain, whereas convective rain depth is larger than stratiform rain depth for heavy rain.

Figure 2 shows mean convective and stratiform rain rates varying with rain depth over different 10° (lon.) ×5° (lat.) boxes of Southeast Asia based on 10-yr TRMM data. Unlike those in Fig. 1, Fig. 2 reveals that surface rain rate is not proportional to rain depth. For stratiform rain, the surface rain rate actually decreases with an increase in rain depth over most areas of Southeast Asia, while the rain depth is larger than 9 km. Over Northwest China and the Tibetan Plateau, the convective rain rate decreases while its rain depth is extremely large. This indicates a complicated relationship between rain depth and surface rain rate. A heavy surface rain rate occurs usually in a deep rain

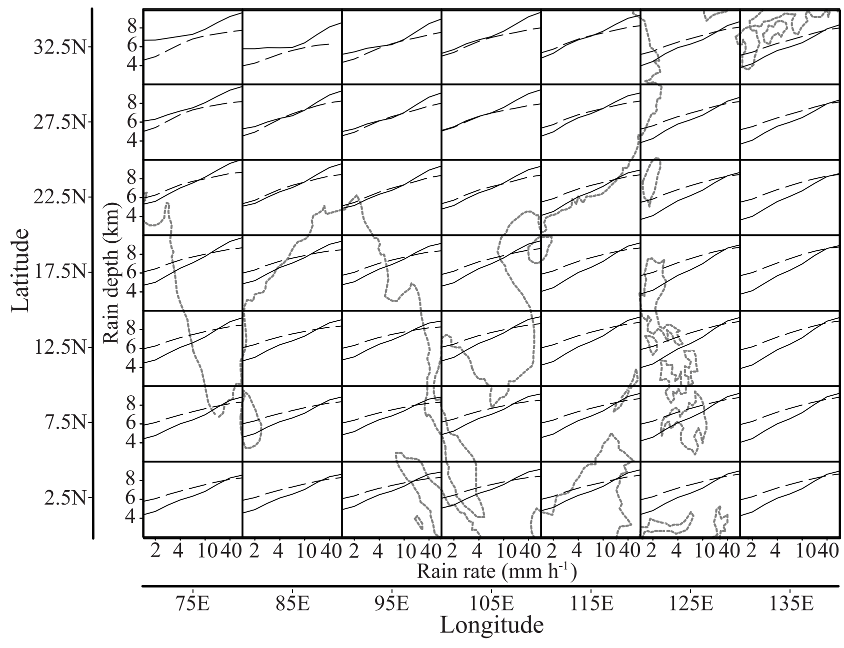

Fig. 1. Mean convective and stratiform rain depth varying with surface rain rate in 49 boxes [10° (lon.)×5°(lat.)] over Southeast Asia. The solid and dashed lines represent convective and stratiform rain, respectively. The x-axis is the rain rate and the y-axis is the rain depth for each box.

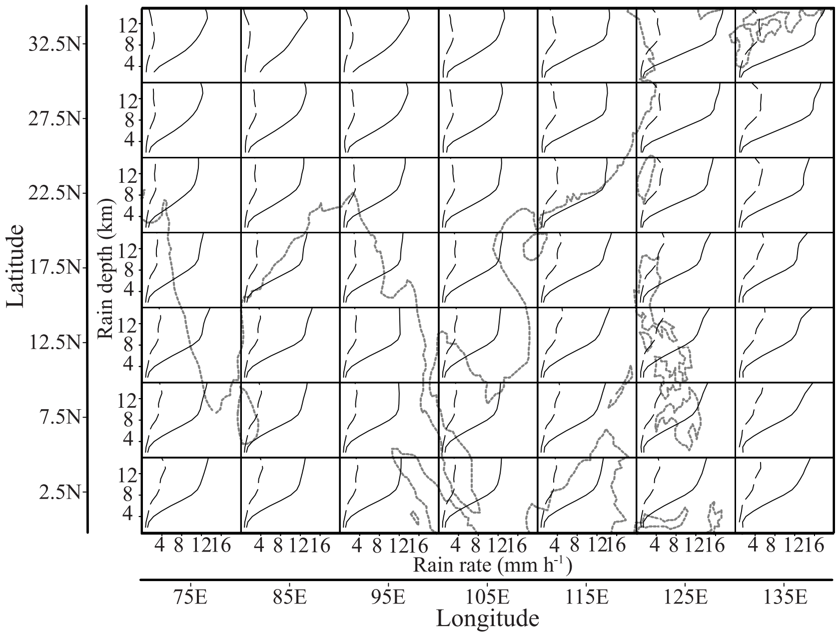

Fig. 2. Same as Fig. 1, except for mean convective and stratiform rain rate varying with rain depth. The x and y axes for each box are surface rain rate and rain depth, respectively.

system, but a deep rain system may not be bringing heavy surface rainfall. These results do not agree with previous results (e.g. Fu and Liu, 2003; Hu et al., 2010a).

From Figs. 1 and 2 we know the relationship between rain depth and surface rain rate of a precipitation system differs from region to region. For the same rain depth, the smallest stratiform rain rate appears over Northwest China and the Tibetan Plateau, while the highest stratiform rain rate could occur over the Northwest Pacific and Indian Ocean (Fig. 2). In coastal and central areas of southern China, and over Indo-China Peninsula and Indian Peninsula, a moderate stratiform rain rate can be observed. This phenomenon is not apparent for convective rain, for the convective rain systems with the same rain depth have similar surface rain rates over different regions.

We noticed the relationships between surface rain rate and rain depths are different over land and the ocean for both convective and stratiform rain. Two areas were selected in this study. The first area (25°–35°N; 70°–110°E) represents strong convective rain systems over land (Li et al., 2008), and the second area (0°–10°N; 100°–140°E) denotes strong convective systems over the ocean.

The convective and stratiform rain depths increase as surface rain rate increases over both the ocean and land (Fig. 3a). Over land, for all surface rain rates,

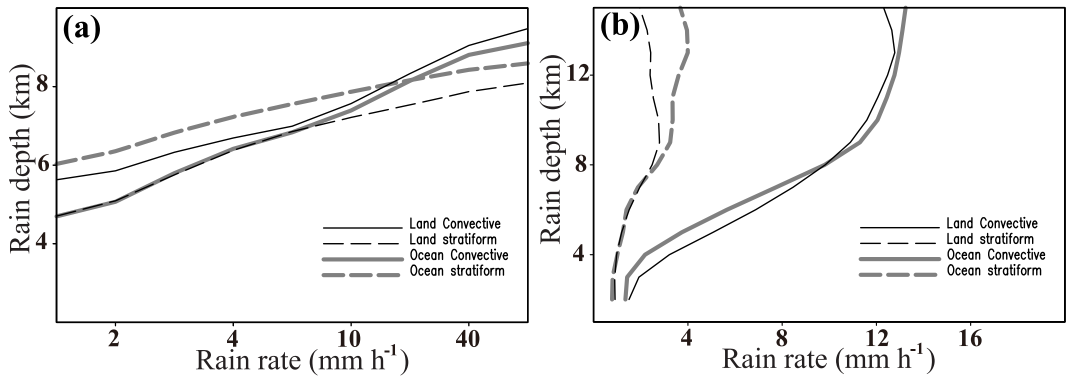

Fig. 3. Mean convective and stratiform rain depth varying with surface rain rate (a), and mean convective and stratiform rain rate varying with rain depth (b) over land and the ocean. Solid and dashed lines denote convective and stratiform rain, respectively. Thin and thick lines denote land and ocean cases, respectively.

the convective rain depth is larger than the stratiform. Over the ocean, the convective rain depth is larger than the stratiform only for rain rates less than 20 mm h^{-1}, whereas the stratiform rain depth is even larger than the convective rain depth for rain rates higher than 20 mm h^{-1}. The convective rain depth is larger over land than the ocean, which implies that convective rain systems are more likely to develop over land than over the ocean. On the other hand, for intense rain systems, stratiform rain depth is even larger over the ocean, which implies that stratiform rain systems can extend to higher altitudes over the ocean.

In Fig. 3b, it can be seen that for the rain systems with a rain depth less than 9 km, the convective rain rate is higher over land than the ocean, while the stratiform rain rates are similar over land and the ocean. For the rain systems with a rain depth greater than 9 km, both convective and stratiform rain rates are higher over the ocean than land. For a relatively shallow convective rain system, its surface rain rate depends on the local dynamic and thermodynamic structures since the quantity of water vapor is sufficient. Compared to adiabatic heating over the sea, non-uniform adiabatic heating is much stronger on land, and so convective rain systems over land become unstable more easily and their upward motion is stronger than over the ocean such that the associated rain rates are higher over land. Water vapor plays an important role in the stratiform rain rate. For a shallow stratiform rain depth, the ample supplies of water vapor lead to a similar stratiform rain rate over both the ocean and land. When a stratiform rain system develops vertically, its rain extends to a high altitude and its surface rain rate largely depends on the availability of local water vapor. Apparently, the oceanic area has more water vapor supply than land areas, which explains why the surface rain rate is higher over the ocean than land. The surface rain rate increases rapidly with increasing rain depths while the depth is less than 9 km. The increase in rain rate becomes slow, and in some cases the rain rate even decreases when the rain depth is greater than 9 km.

4. Probability distributions of rain depth and rain rate

To further understand the relationship between rain depth and surface rain rate, we conducted statistical analyses for convective and stratiform rain depths and surface rain rates over land and ocean with the Probability Density Function (PDF) and Cumulative probability Density Function (CDF) as tools (Li et al., 2008).

In Fig. 4, the PDF (left panel) and CDF (right panel) are shown for convective rain over land (upper panel) and the ocean (lower panel). For convective rain systems, the probability of lower rain rates is the highest over both land and the ocean (Figs. 4a, c). Figures 4b and d show that surface rain rate in a rain system with a CDF of more than 50% is always lower than 36 mm h^{-1} regardless of the rain depth. The CDF in shallow rain systems with a surface rain rate lower than 36 mm h^{-1} is even larger. For example, in a rain system with a rain depth of less than 3 km, the probability of the surface rain rate being lower than 36 mm h^{-1} is in excess of 95%. This indicates that the shallower a rain system is, the more probable it is that the surface rain rate will be lower. When a rain system becomes deeper, the probability of a high surface rain rate becomes larger; however, the largest probability is still for a small surface rain rate. The largest probability in terms of surface rain rate occurs for a relatively small rain rate, regardless of the rain depth.

The distributions of PDF and CDF appear in similar patterns over land and the ocean. The probability of strong convective rain over the ocean is slightly larger than over land, but only when the rain system is relatively deep. For example, for a rain system with a rain depth greater than 14 km, the probability of the surface rain rate being lower than 72 mm h^{-1} over land is about 90% (Fig. 4b), which means the probability of the surface rain rate being higher than 72 mm h^{-1} over land is only about 10%, whereas the probability of the surface rain rate being higher than 72 mm h^{-1} over the ocean is in excess of 17% (Fig. 4d).

By the same token, the largest probability occurs for low rain rates for stratiform rain systems, over both land and the ocean (Figs. 5a, c). The probability decreases with an increasing rain rate. When the rain rate is lower than 9 mm h^{-1}, the probabilities of different rain depths are similar. When the rain rate is higher than 9 mm h^{-1}, the largest probability does not occur for the deepest rain system. Instead, it appears for rain systems with a moderate rain depth, which is consistent with the results shown in Fig. 3b. Figures 5b and d show that the CDF for rain systems with a rain rate lower than 6 mm h^{-1} is about 50%, regardless of the rain depth. The probabilities of relatively deep and shallow rain systems are significantly larger than 50%. This suggests that the surface rain rate of a stratiform rain system, similar to a convective rain system, is usually small regardless of its rain depth. Compared to convective rain, the probability of a strong rain rate is much smaller in stratiform rain. The comparison between PDF and CDF for stratiform rain systems reveals that the probability of a strong surface rain rate is slightly higher over the ocean than

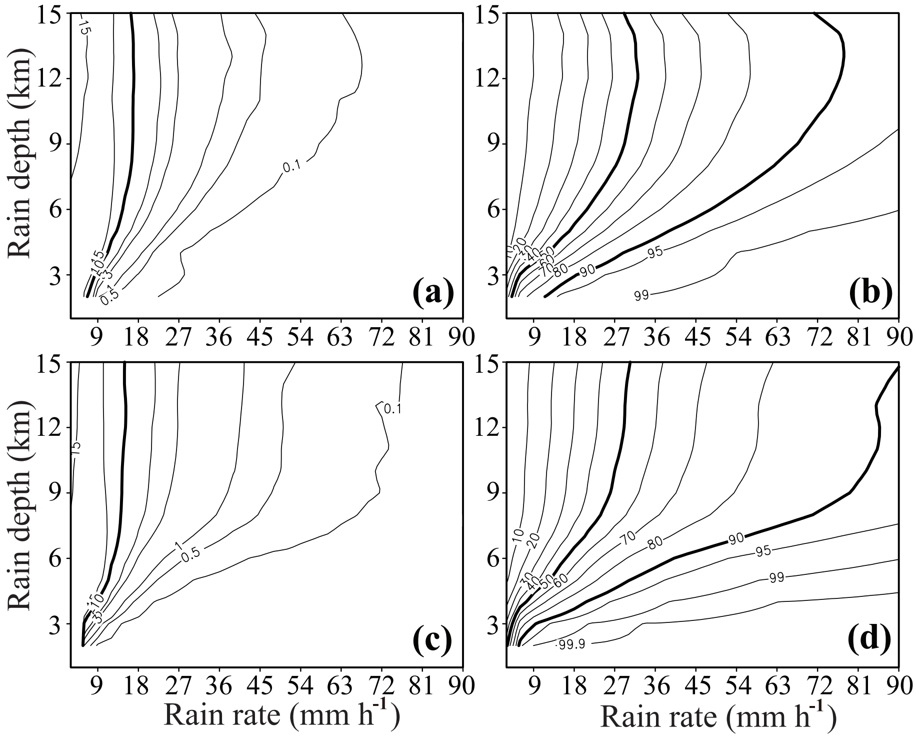

Fig. 4. PDF (left panel) and CDF (right panel) for convective rain over land (upper panel) and the ocean (lower panel). The PDF contours are labeled at 0.1%, 0.5%, 1%, 3%, 5%, 10% and 15% with the contour at the 10% line highlighted. The CDF contours are labeled at 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95%, 99%, and 99.9% with the 50% and 90% lines highlighted.

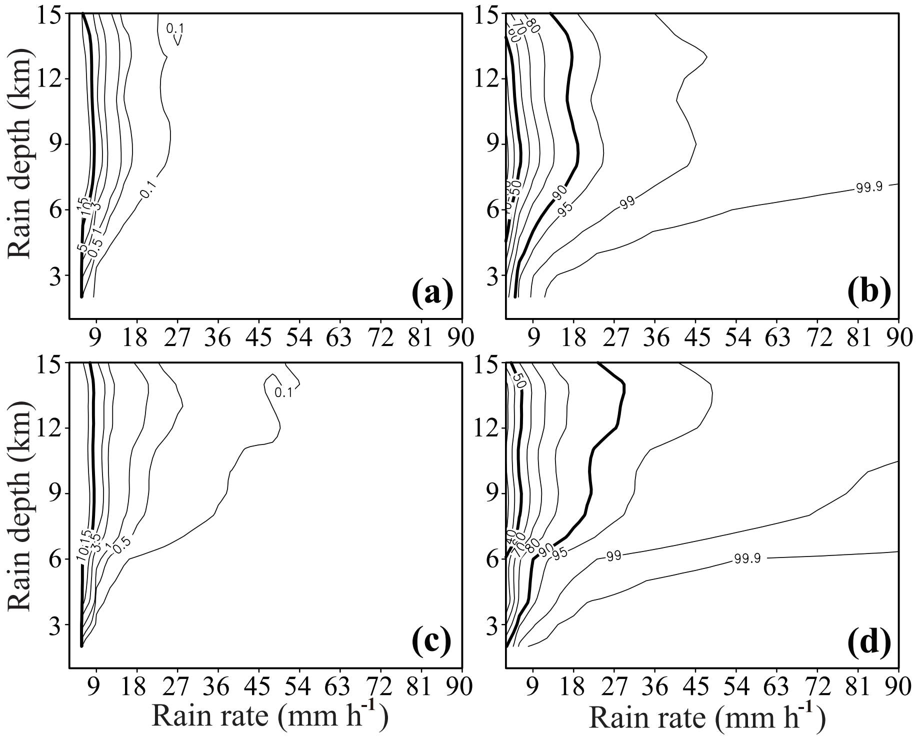

Fig. 5. Same as Fig. 4, except for stratiform rain.

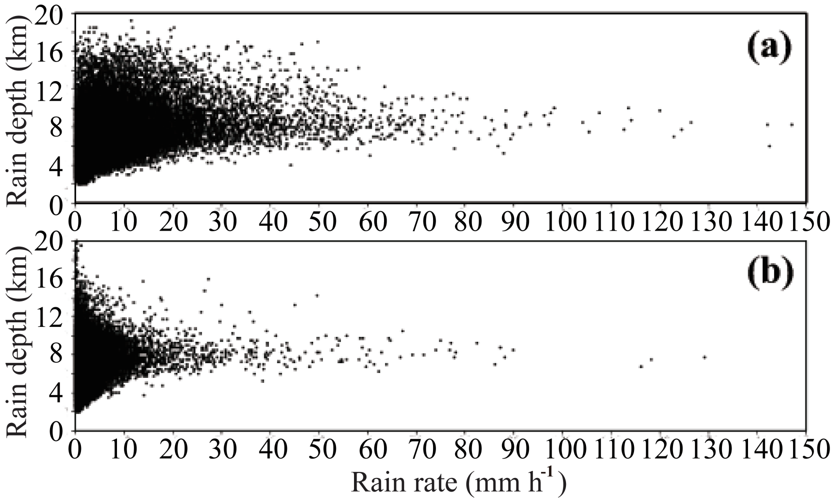

Fig. 6. Scatter plot of surface rain rate versus rain depth for convective rain (a) and stratiform rain (b) over Southeast Asia in March 2000.

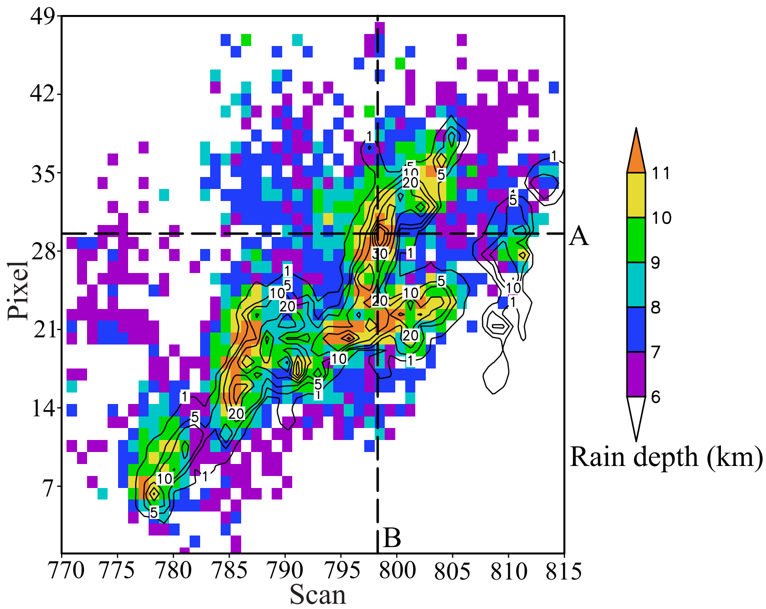

Fig. 7. The distributions of rain depth (shaded; km) and surface rain rate (contour; mm h^{-1}) observed by TRMM-PR orbit 13476 on 31 March 2000. The two dashed straight lines (A and B) cross the rain center.

land.

The rain depth increases with an increasing surface rain rate, but the surface rain rate may not increase as its rain depth increases. In fact, a rain system may have a weak surface rain rate regardless of its rain depth. Thus, it is highly possible that a small surface rain rate could appear in a deep rain system.

5. Case study

A scatter plot of surface rain rate versus rain depth for March 2000 over Southeast Asia is taken as an example to study their relationship (Fig. 6). The results show that convective rain depth has a larger spread of data points than stratiform rain depth, indicating a larger variation in convective rain depth with the associated surface rain rate. The results also confirm that, for various rain depths, the major surface rain rate is less than 10 mm h^{-1} and 30 mm h^{-1} for stratiform and convective rain systems, respectively. The mean rain depth for convective and stratiform rain systems is about 8 km.

Figure 7 shows horizontal distributions of rain depth and rain rate for a rain event on 31 March 2000. It is clearly shown that the relative maximum centers

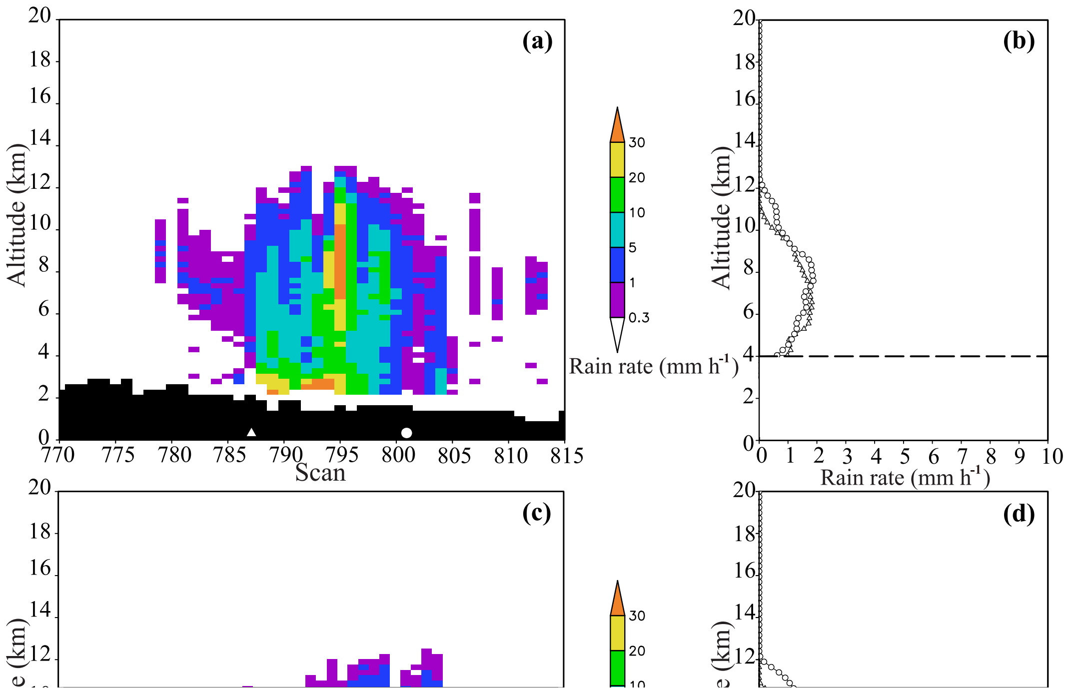

Fig. 8. TRMM-PR reflectivity profiles for (a) along track at pixel position 30, i.e. line A in Fig. 7; and (c) cross track at scan number 799, i.e. line B in Fig 7. The profiles of two convective rain (triangles) and stratiform rain (circles) are shown in (b) and (d). The mean profiles below 4 km are not shown for clear plots in Figs. 8b and d.

of rain depth and rain rate are generally well collocated. The areas with large surface rain rates have large rain depths; however, some areas of deep rain do not have a large surface rain rate. This suggests that a deep rain system is a favorable condition for a strong surface rain rate, but such a deep rain system is not always associated with a strong surface rain rate. To further explain this feature, two cross sections along the dashed lines in Fig. 7 are plotted in Fig. 8.

Although rain depths are greater than 10 km in the two convective rain cases (triangles) and the two stratiform rain cases (circles) in Fig. 8, their associated surface rain rates are small. The rain rates for the two stratiform cases and the first convective case are less than 1 mm h^{-1}, and for the second convective case it is less than 2.7 mm h^{-1}. The advection and entrainment/detrainment lead to the outward extension of rain at high altitudes, which forms anvil rain clouds surrounding the strong convective centers. These are actually weak convective and stratiform systems whose rainfall seldom reaches the surface due to evaporation. This process explains why sometimes a deep rain system might not give rise to a strong surface rain rate.

6. Mean rain profiles

Analysis of Figs. 2 and 3b demonstrated that the surface rain rate increases rapidly with an increasing rain depth when it is less than 9 km, whereas the increase in rain rate becomes slow and even decreases with an increase in rain depth when it is above 9 km. Thus, we further classified rain systems into two categories of rain depth: deep systems ($\geqslant$9 km), and shallow systems (<9 km).

Figures 9 and 10 present TRMM-PR radar reflectivities with the "contoured frequency by altitude diagrams" (CFAD) method, initially applied by Yuter and Houze (1995). The deep convective rain reflec-

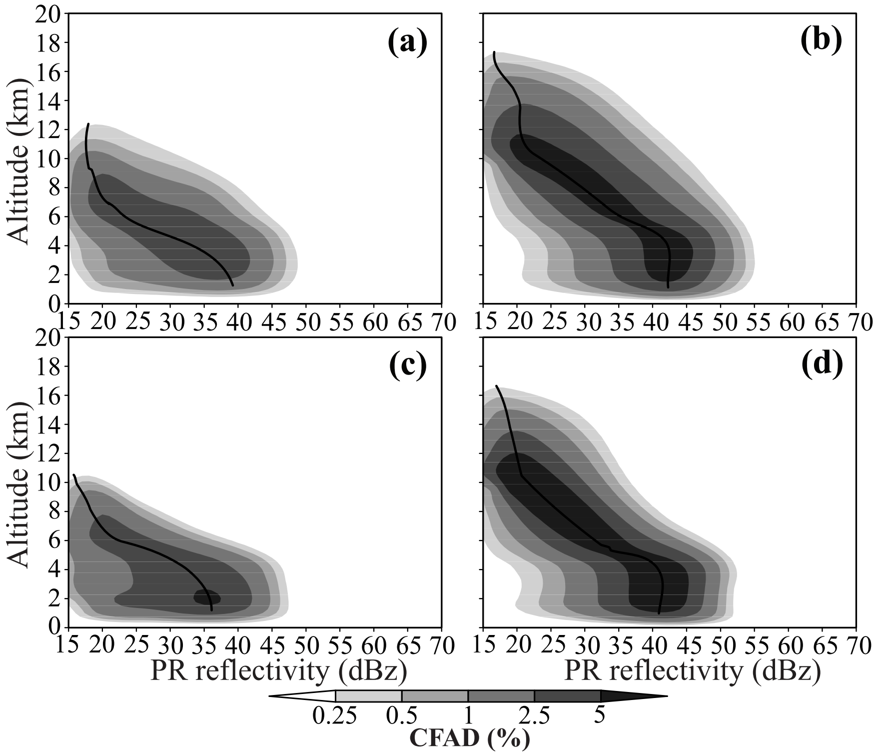

Fig. 9. CFAD of TRMM-PR reflectivity associated with convective rain over land (upper panel) and the ocean (lower panel) for rain depth less than 9 km (left panel) and greater than 9 km (right panel). The dark solid line in each panel represents its mean reflectivity profile.

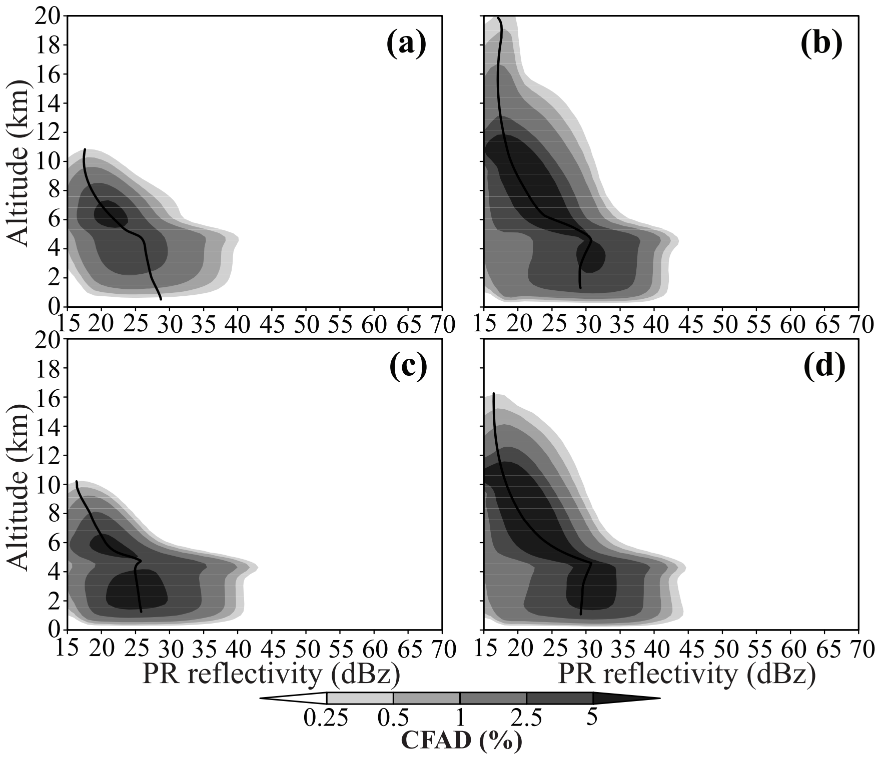

Fig. 10. Same as Fig. 9, except for stratiform rain.

tivity profiles (Figs. 9b, d) can be vertically categorized into three sections: surface–4.5 km; 4.5–10 km; and 10–20 km. The reflectivity profile has an almost constant, rapid decrease, and a slow rate of decrease for low, middle and upper sections, respectively. The mean reflectivity profiles over the ocean (Fig. 9d) and land (Fig. 9b) are generally similar; however, their differences are also obvious. The low section is about 2 dBZ stronger, while the middle section rate of decrease is slower over land than the ocean. For the upper section, the reflectivity gradually decreases over the ocean, while remaining almost constant between 10 and 15 km over land.

For shallow convective systems over land (Fig. 9a) and the ocean (Fig. 9c), their vertical profiles can also be classified into three sections: lower (<3 km); middle (3–6 km) and upper section (>6 km). Over the ocean (Fig. 9c), the reflectivity intensity decreases quickly in the upper section, but decreases slowly in the middle section. In the lower section, its intensity is about 36 dBZ. Over land (Fig. 9a), the reflectivity intensity is almost constant in the 9–12 km altitude range, but decreases rapidly from 6 to 9 km. In the middle section it increases, and also increases slightly in the lower section. In addition, reflectivity for deep and shallow systems near the surface is about 40 dBZ and 35 dBZ over the ocean, and 43 dBZ and 39 dBZ over land, respectively.

By the same token, reflectivity profiles for stratiform rain systems are shown in Fig. 10. The mean reflectivity profiles of deep stratifrom rain systems over the ocean (Fig. 10d) and land (Fig. 10b) are similar, showing distinct lower (surface–4.5 km), middle (4.5–10 km), and upper sections (10–20 km). In the lower section, there is a slight decrease in reflectivity from 4.5 km to the surface. There is a gradual increase in reflectivity intensity in the middle section, while the reflectivity in the upper section is almost constant. For shallow systems (Figs. 10a, c), there are only upper (4.5–11 km) and lower (4.5 km–surface) sections. The reflectivity in the lower section is almost constant over the ocean (Fig. 10c), but increases over land (Fig. 10a). There is an obvious increase in reflectivity from 11 km to 4.5 km. Both deep and shallow stratiform rain systems have a relatively strong reflectivity layer around 4.5 km, which is the unique bright band feature of stratiform rain systems.

Comparing Figs. 9 with 10 reveals that the main differences between deep convective and stratiform rain systems can be found at 4.5 km, and up to 19 km. The stratiform system has a bright band around 4.5 km and a weak increasing rate of reflectivity from 10 km to 4.5 km, while the convective rain system has no bright band and a large increasing rate of reflectivity from 10 km to 4.5 km, resulting in a stronger surface reflectivity for convective systems. For shallow systems, there are also distinct differences between convective and stratiform systems. There is mainly a two-section reflectivity profile for stratiform systems, but a three-section profile for convective systems.

7. Conclusions

Ten-year TRMM 2A25 data have been used to study the relationships between convective and stratiform rain depths and their associated surface rain rates over Southeast Asia. The main conclusions from the results are as follows:

(1) The mean convective or stratiform rain depth increases with increasing surface rain rate; however, the surface rain rate may not increase correspondingly with an increase in rain depth. In general, a rain system with a strong surface rain rate is a deep rain system. In contrast, a deep rain system may not have a large surface rain rate. The relationships between rain depth and surface rain rate are different over different regions. Over land, conditions are more favorable for the development of convective rain than over the ocean, whereas stratiform rain may extend to higher altitudes than convective rain does over the ocean.

(2) The relationship between rain depth and its associated surface rain rate is generally complex. For a convective rain system, the probability of a strong surface rain rate increases as its rain depth increases. For a stratiform rain system, the probability of a strong surface rain rate first increases and then decreases as its rain depth increases. Both weak convective and stratiform surface rain rates have the largest probabilities, regardless of their rain depths. The probability of strong convective rain is much higher than strong stratiform rain, whereas the probability of an extremely strong surface rain rate is higher over the ocean than land.

(3) Precipitation is a very complex process, encompassing various cloud microphysical processes. Rain depth is a parameter showing one aspect of rain vertical structure, and it is not well related to the associated surface rain rate. Results from this study demonstrate that precipitation microphysical processes need to be better understood in order to predict surface rain rates more accurately.

(4) Both deep convective and stratiform rain reflectivity profiles can be vertically categorized into three sections: surface–4.5 km; 4.5–10 km; and 10–20 km. The main differences between deep convective and stratiform rain are located at 4.5 km, and up to 19 km. Stratiform systems have a bright band around 4.5 km and a weak rate of increase in reflectivity from 10

km to 4.5 km, while convective rain systems have no bright band and a large rate of increase in reflectivity form 10 km to 4.5 km. For shallow systems, there is mainly a two-section reflectivity profile for stratiform systems, but a three-section profile for convective systems.

Acknowledgements. The authors would like to thank TRMM TSDIS for providing the TRMM-PR 2a25 datasets. Help from Dr. Xiaofan LI at NOAA/NESDIS during the preparation of this paper is also appreciated. This study was funded by four special grants from the National Natural Science Foundation of China (Grand Nos. 41175046, 41205030, 40428002 and 41105028) and the Special Funds for Scientific Research on Public Causes of China (Meteorology) (Grand No. GYHY200906002).

REFERENCES

Awaka, J., T. Iguchi, and K. Okamoto, 1998: Early results on rain type classification by the Tropical Rainfall Measuring Mission (TRMM) precipitation radar. *Proc. 8th URSI Commission F Open Symp.*, Averior, Portugal, 134–146.

Du, B., and Z. Gao, 1998: An investigation on vertical profiles of radar reflectivity and precipitation estimation with remotely sensed data. *Journal of Nanjing Institute of Meteorology*, **21**, 729–736. (in Chinese)

Fu, R., L. Hu, G. J. Gu, and Y. D. Li, 2008: A comparison study of summer-time synoptic-scale waves in South China and the Yangtze River Basin using the TRMM multi-satellite precipitation analysis daily product. *Science in China* (*D*), **51**(1), 114–122.

Fu, Y. F., 2006: Precipitation structures of a thermal convective system happened in the central Western Subtropical Pacific Anticyclone. *Acta Meteorologica Sinica*, **20**, 232–243.(in Chinese)

Fu, Y. F., and G. S. Liu, 2001: The variability of tropical precipitation profiles and its impact on microwave brightness temperatures as inferred from TRMM data. *J. Appl. Meteor.,* **40**, 2130–2143.

Fu, Y. F., and G. S. Liu, 2003: Precipitation characteristics in mid-latitude East Asia as observed by TRMM PR and TMI. *J. Meteor. Soc. Japan*, **81**(6), 1353–1369.

Fu, Y. F., Y. H. Lin, G. S. Liu, and Q. Wang, 2003: Seasonal characteristics of precipitation in 1998 over East Asia as derived from TRMM PR. *Adv. Atmos. Sci.*, **20**(4), 511–529, doi: 10.1007/BF02915495.

Fu, Y. F., G. S. Liu, G. X. Wu., R. C. Yu, Y. P. Xu, Y. Wang, R. Li, and Q. Liu, 2006: Tower mast of precipitation over the central Tibetan Plateau summer. *Geophys. Res. Lett.*, **33**, doi: 10.1029/2005GL024713.

Hu, L., S. Yang, and Y. D. Li, 2010a: Diurnal and seasonal climatology of precipitation depth over Tibetan Plateau and its downstream regions. *Chinese J. Atmos. Sci.*, **34**(2), 387–392.

Hu, L., S. Yang, Y. D. Li, and S. T. Gao, 2010b: Diurnal variability of precipitation depth over Tibetan Plateau and its surrounding regions. *Adv. Atmos. Sci.*, **27**(1), 115–122, doi: 10.1007/s00376-009-8193-5.

Kodama, Y. M., and A. Tamaoki, 2002: A re-examination of precipitation activity in the subtropics and the mid-latitudes based on satellite-derived data. *J. Meteor. Soc. Japan*, **80**, 1261–1278.

Kummerow, C., and Coauthors, 2000: The status of the Tropical Rainfall Measuring Mission (TRMM) after two years in orbit. *J. Appl. Meteor.*, **39**, 1965–1982.

Li, J., and J. Luo, 2006: Estimation of rainfall of stable stratiform clouds with radar echo features. *Meteorological Monthly*, **32**, 34–39. (in Chinese)

Li, Y. D., Y. Wang, S. Yang, L. Hu, S. T. Gao, and R. Fu, 2008: Characteristics of summer convective systems initiated from Tibetan Plateau. Part I: Origin, track, development and precipitation. *J. Appl. Meteor. Climatol.*, **47**(10), 2679–2695.

Liu, C., and E. J. Zipser, 2009: "Warm rain" in the tropics: Seasonal and regional distribution based on 9 years of TRMM data. *J. Climate*, **22**(1), 767–779.

Liu, G., and T. Takeda, 1989: Two types of stratiform precipitating clouds associated with cyclones. *Tenki,* **36**, 147–157. (in Japanese)

Liu, Q., and Y. F. Fu, 2007: Study of rainfall of summer in Asia based on TRMM/TMI. *Science in China* (*D*), **37**(1), 111–122. (in Chinese)

Xu, Y., 1992: Radar echo features and their relations to rainfall for heavy frontal rains in the Pearl River Delta. *Journal of Tropical Meteorology*, **8**, 174–180. (in Chinese)

Yang, S., and E. A. Smith, 2008: Convective-stratiform precipitation variability at seasonal scale from eight years of TRMM observations: Implications for multiple modes of diurnal variability. *J. Climate*, **21**, 4087–4114.

Yang, S., K. S. Kuo, and E. A. Smith, 2008: Persistent nature of secondary diurnal modes in both land and ocean precipitation. *J. Climate*, **21**, 4115–4131.

Yuter, S. E., and R. A. Houze, 1995: Three-dimensional kinematic and microphysical evolution of Florida cumulonimbus. Part II: Frequency distributions of vertical velocity, reflectivity, and differential reflectivity. *Mon. Wea. Rev.*, **123**, 1941–1963.

Zipser, E. J., and K. R. Lutz, 1994: The vertical profile of radar reflectivity of convective cells: A strong indicator of storm intensity and lightning probability. *Mon. Wea. Rev.*, **122**, 1751–1759.