Comparing Occurrences and Vertical Structures of Hydrometeors between Eastern China and the Indian Monsoon Region Using CloudSat/CALIPSO Data

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ABSTRACT

Seasonal variations in the occurrence frequency, vertical location, and radar reflectivity factor (dBZ) of hydrometeors covering eastern China and the Indian monsoon region are described using two CloudSat standard products [Geometrical Profiling Product (GEOPROF) and GEOPROF-lidar] during the period July 2006–August 2007. The 14-month averaged hydrometeor occurrence frequency is 80% (for eastern China) and 70% (for Indian region), respectively, to which multilayer (mostly double or triple layers) hydrometeors contribute 37% and 47%. A significant increase in the multilayer hydrometeor amount from winter to summer in the Indian region causes a pronounced seasonal variation in its total hydrometeor amount. The nearly opposite phases in the seasonal variations of single- and multilayer hydrometeor amounts result in little change with season in total hydrometeor amount in eastern China. Although the passive sensor-based satellite cloud product is able to provide the major seasonal features in the hydrometeor occurrence frequency (HOF) as revealed by the CloudSat/Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) product, it generally underestimates the HOF.

The maxima in the amounts of both high-level and thick hydrometeor layers occur during summer in both regions, reflecting the impact of the Asian summer monsoon. The abundance of low-level cloud layers and scarcity of hydrometeors at higher levels in eastern China during autumn to winter reflect the general subsidence motion in the middle and upper troposphere. The hydrometeors are geometrically thin in both regions. Cirrus containing small ice crystals is the most common cloud type in the Indian region over the year, while the eastern China hydrometeors are located lower and distributed more evenly in the dBZ–altitude phase space. Although the Indian region has deeper convection and more anvils than eastern China during summer, the averaged dBZ–altitude distributions of deep convection and anvils are nearly identical between the two regions.

1. Introduction

Hydrometeors (e.g., clouds and precipitation) play an important role in the energy and moisture balances of earth by affecting radiative transfer and microphysical processes. General circulation models (GCMs) are major tools for future climate projection. However, hydrometeors are poorly simulated by GCMs (e.g., Zhang et al. 2005; Bony et al. 2006). Cloud feedbacks have been confirmed as a primary source of the intermodel differences in equilibrium climate sensitivity in the most recent Intergovernmental Panel on Climate Change (IPCC) report (Randall et al. 2007). One of the major reasons for the poor representation of hydrometeors in GCMs is a lack of knowledge on the vertical distribution and internal structure of hydrometeor layers.

On 28 April 2006 the U.S. National Aeronautics and Space Administration launched a pair of active remote sensors to measure the vertical structure of hydrometeors and aerosols from space. CloudSat (Stephens et al. 2002), carrying the Cloud Profiling Radar (CPR) (Im et al. 2006), and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO; Winker et al. 2003), fielding the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) (Winker et al. 2007), were inserted into nearly identical orbits, where they joined the A-Train constellation (Stephens et al. 2002) of three other earth-orbiting satellites: Aqua, Aura, and Parasol. The formation of A-Train has made it possible...
to make a global survey of the vertical structure of hydrometeors and aerosols and their physical properties.

Since becoming available in the middle of June 2006, the CloudSat and CALIPSO data have been used to investigate hydrometeor properties (e.g., Haynes and Stephens 2007). For example, Mace et al. (2007) documented global distribution of cloudiness using the CloudSat Geometrical Profiling Product (hereafter GEOPROF) during the first summer of CloudSat operation. The vertical distribution of zonally averaged hydrometeor occurrence showed the relationship of clouds with components of the atmospheric general circulation. Zhang et al. (2007) investigated the mesoscale patterns of cloud and precipitation radar reflectivity using 84-day CloudSat GEOPROF data to identify distinct tropical cloud regimes via a cluster analysis. They also demonstrated the links between clouds and the atmospheric circulation using the monthly mean vertical velocity at 500 hPa as an indicator. (Moreover, a Journal of Geophysical Research special CloudSat section is currently in review.)

A general motivation of the present study is the fact that there have been few investigations on hydrometeor vertical structure in the Asian region. As the Asian monsoon is one of the most significant components of the global climate system (e.g., Wang et al. 2005), GCMs are unlikely to make correct climate projections if cloud systems in the Asian region are not reasonably represented in the models.

The present study is more directly motivated by a previous study of Yu et al. (2001, hereafter Y01). Utilizing the data from the International Satellite Cloud Climatology Project (ISCCP) (Rossow and Schiffer 1991, 1999) and Earth Radiation Budget Experiment (ERBE) (Barkstrom 1984) from February 1985 to December 1989, Y01 compared cloud fractions and cloud radiative forcings (CRFs) between two subregions of the Asian monsoon region: eastern China (20°–35°N, 102.5°–122.5°E) and the Indian monsoon region (10°–25°N, 70°–90°E). The major conclusions drawn by Y01 are as follows. Both the annual mean and the seasonal variation of cloud amount and CRF differ significantly between the two regions, although the seasonal cycles of rainfall are in phase. In the Indian region, the high-, mid-, and low-top clouds have similar phase structure of their seasonal cycle. The maximum cloud fraction occurs in the summer monsoon period and high-top clouds dominate the total cloud fraction, resulting in a maximum of net negative CRF in summer. In eastern China, it is the mid- and low-top clouds rather than high-top clouds that dominate the total cloud fraction. The maximum cloud fraction occurs in spring. As a result, the maximum of net negative CRF occurs in early summer in eastern China. The annual mean negative net CRF in eastern China is larger than that in the Indian region, mainly due to the larger amounts of clouds with tops located at mid and low levels in eastern China during all of the year except for summer.

The Asian summer monsoon is demarcated into three subsystems in the literature: the Indian summer monsoon (ISM), the eastern Asian summer monsoon (EASM), and the western North Pacific summer monsoon (WNPSM) (e.g., Wang and LinHo 2002; Ding 2007). Although these monsoons are closely related (e.g., Zhang 2001), it is believed that the EASM is a subtropical monsoon in which the low-level winds reverse primarily from winter northerlies to summer southerlies, whereas the ISM and WNPSM are tropical monsoons in which the low-level winds reverse from winter easterlies to summer westerlies (e.g., Wang et al. 2005; Ding 2007). The eastern China and Indian monsoon regions in the present study and Y01 are subregions of the EASM region and the ISM region, respectively.

The major objective of the present study is to advance the understanding of hydrometeor occurrences and vertical structures in the eastern China and the Indian monsoon regions using the CloudSat/CALIPSO data. More specifically, seasonal variations in occurrence frequency and location of single- and multilayer hydrometeors, average reflectivity distributions of all cloudy profiles during each season, and average reflectivity distributions of summertime deep convective profiles and anvils are analyzed and compared between the two regions. It is hoped that these results will be useful for future GCM evaluation and improvement.

Sections 2 and 3 describe the datasets and methodology, respectively. Analyses results are presented in sections 4 to 6, including occurrences of hydrometeor layers (section 4), thickness, top height and base height of hydrometeor layers (section 5), and radar reflectivity factors (section 6). Section 7 contains the summary and conclusions.

2. Data

Two CloudSat standard data products, publicly available as the level 2 GEOPROF and GEOPROF-lidar products, are used in the present study. A concise description of the two products is given below. Detailed information about the CloudSat products can be found in the CloudSat Data Products Handbook (available online at http://www.cloudsat.cira.colostate.edu/dataHome.php).

a. GEOPROF data

Produced using the algorithm described by Marchand et al. (2008), the GEOPROF product identifies those
levels in the vertical column sampled by CloudSat that contain significant radar echoes from hydrometeors (i.e., the CPR cloud mask) and provide an estimate of the radar reflectivity factor for each of these volumes. A major input to the algorithm is the CPR measured backscattered power as a function of distance from the CPR on CloudSat. Flying in a sun-synchronous orbit at an 89° inclination angle and a nominal altitude of 705 km, the along-track velocity of the CPR instrument is approximately 7 km s$^{-1}$. This velocity combined with the sample rate of 0.16 s per profile generates a CPR profile every 1.1 km along track. However, 688 pulses per burst are averaged to produce a nominal footprint of 2.5 km along track. The CloudSat antenna pattern provides an instantaneous footprint of approximately 1.4 km across track at mean sea level. The CPR emits a pulse of 3.3 microseconds duration, leading to a vertical resolution of approximately 480 m. The backscattered signal is oversampled to produce a range gate spacing of 240 m. Each profile has 125 vertical bins for a total vertical window of 30 km. The volume defined by the 2.5 km by 1.4 km footprint and the 240-m range bin is referred to as a radar range resolution volume (RRV). A CPR cloud mask of 20–40 represents that hydrometeors are detected in the RRV. The CPR minimum detectable signal is $-28$ dBZ. Each GEOPROF data file contains one complete granule, that is, one orbit of data (approximately 40 022 km) beginning at the first profile on or after the equator on the descending node.

b. GEOPROF-lidar data

With the ability of the CPR to probe optically thick large-particle layers and the ability of the CALIOP to sense optically thin layers and tenuous cloud tops, the two instruments have the potential of providing a complete picture of the occurrence of cloud and aerosol. The GEOPROF-lidar product is produced by extracting maximum information from the combined radar and lidar sensors. The most important information provided by the GEOPROF-lidar product is the location of hydrometeor layers in the vertical column. That is, the number of hydrometeor layers and the locations of their tops and bases above mean sea level. The maximum number of hydrometeor layers is up to five. This information is extremely difficult to derive based on measurements from passive instruments alone. The GEOPROF-lidar product also provides an estimate of the fraction of lidar volumes in a CPR RRV that contains hydrometeors, namely “cloud fraction.” Each GEOPROF-lidar data file contains one orbit of data at the spatial grid of the CPR.

3. Methodology

The hydrometeor occurrence information contained in GEOPROF-lidar is used to discriminate between cloudy and clear profiles. That is, a profile is considered cloudy if there is at least one hydrometeor layer in the column. The monthly occurrence frequencies of single-, double-, triple-, four-, and five-layer hydrometeors are determined as the number of profiles containing single, double, triple, four, and five hydrometeor layers, respectively, divided by the total number of profiles collected in the horizontal domain within the month. The total occurrence frequency of hydrometeor layers is the sum of the frequencies of all hydrometeor-layer types. To examine seasonal variation and vertical distribution of the hydrometeor layers, the GEOPROF cloud mask and the GEOPROF-lidar cloud fraction are combined to determine the cloud fractions in each vertical 1-km bin for individual pixels. The cloud fraction is set to 100% for a cloud mask of 20–40 and otherwise equals the maximum cloud fraction in the vertical interval. The monthly hydrometeor amount is then calculated as the average cloud fraction in the vertical interval within the month. The monthly averaged numbers of satellite overpass are 39 (eastern China) and 37 (the Indian region) and those of pixels are 55 597 and 53 503.

In the ISCCP datasets, the high-, mid-, and low-top clouds were defined by cloud-top pressure ($P_{ct}$) with a $P_{ct}$ of 440 and 680 hPa, respectively, to separate high from midlevel and midlevel from low level. Note that the ISCCP algorithms identify one cloud layer at a time in the column, meaning that lower clouds underneath higher clouds could not be identified (Rossow and Garder 1993). To compare with the cloud amount statistics based on the ISCCP data (Y01), monthly occurrence frequencies of high-, mid-, and low-topped hydrometeors are also determined with the GEOPROF-lidar data, including the uppermost cloud layers only to consider the obscuring effect on lower clouds by higher clouds, as in the ISCCP. Here high level is defined as above 6 km, midlevel between 3 and 6 km, and low-level below 3 km.

Yuter and Houze (1995) successfully employed a statistical technique, contoured frequency by altitude diagram (CFAD), to display the statistical distributions of the storm properties. However, the CFAD method has a side effect of increasing the percentages at the altitudes where there are fewer data points. To overcome such weakness, we construct normalized CFAD of dBZ based on the GEOPROF product to examine the averaged vertical structure of hydrometeors. The method to construct a normalized CFAD is similar to that to construct a CFAD, except for that the frequency
for each box is normalized to the total number of points in all boxes in the dBZ–altitude phase space.

All cloudy profiles are used to construct the normalized CFADs of dBZ for each season in the two analysis regions, respectively. To further study the microphysical structure of deep convective hydrometeors and anvils associated with the Asian summer monsoon, the cloudy profiles during the summer months (June–August of 2006 and 2007) are subsampled. A profile that is considered as deep convective must satisfy the following two criteria: 1) the uppermost hydrometeor layer has a top above 10 km and is at least 10 km thick and 2) the maximum dBZ is greater than 10. Using this definition, we obtained 23 391 and 32 754 profiles for eastern China and the Indian region, respectively. To define a profile as containing anvils, the uppermost hydrometeor layer in the profile must be at least 4 km thick with a top above 10 km and a base above 6 km. By this definition, 85 702 and 147 469 anvil profiles are found for eastern China and the Indian region. These subsampled anvil profiles are used to construct normalized CFADs of dBZ at heights above 6 km; that is, data below 6 km are excluded to ignore lower hydrometeor layers co-occurring with anvils.

The dBZ value in a CPR RRV is considered meaningful and is included to construct the CFADs if the CPR cloud mask in the RRV is 20–40. Otherwise it is not included in the construction of CFADs. The CloudSat CPR has an estimated operational sensitivity of −28 dBZ, which prevents CloudSat from seeing some thin cirrus. As will be shown later, regardless of this drawback, the GEOPROF product is valuable in revealing the major characteristics of hydrometeor internal structures and demonstrating differences and similarities between the two analysis regions. Moreover, no attempt is made by the CloudSat algorithms to distinguish between clouds and precipitation as these would normally be defined.

4. Hydrometeor occurrence frequency

a. Vertical distribution of hydrometeor occurrence

Figure 1 displays the vertical distributions of monthly cloud fraction in eastern China and the Indian region, respectively, during the period of July 2006–August 2007. One striking feature in Fig. 1 is that the distribution of hydrometeor amounts exhibits two peaks during summer in both regions. The first peak is located in the upper troposphere, with a larger value (60%–80%) located at higher altitudes (13–17 km) in the Indian region than that (30%–50%, 12–15 km) in eastern China, indicating deeper and more intense convection in the Indian monsoon region. The second summer peak located at 1–3 km is of 30%–40% (eastern China) or 40%–50% (the Indian region), suggesting occurrences of shallow cumuli and stratocumulus clouds. Moreover, in the Indian region there are 30%–50% hydrometeor amounts at the midlevel (5–10 km) during summer 2007, which could be contributed by stratiform clouds associated with the deep convective systems. The sharp increase of hydrometeor amount in the upper troposphere from May to June of 2007 in both regions suggests that the Asian summer monsoon started to influence the cloud formation processes in these regions in June that year. This is consistent with the fact that the synchronized onset of the Indian rainy season and the mei-yu, which is the major weather system causing heavy rainfall during summer in eastern China, occur in June (e.g., Wang and LinHo 2002).

During the other seasons, there are distinguished characteristics in the cloud amount pattern between the two regions. In eastern China, hydrometeor layers mostly exist at low altitudes (< 5 km), in particular during winter. The abundance of low-level cloud layers
and scarcity of higher-level hydrometeors reflects the general subsidence motion in the middle and upper troposphere. In the Indian region, most hydrometeor layers are located in the low (below 4 km) and upper (10–16 km; mainly during autumn) troposphere, with few occurrences of hydrometeors in the middle troposphere (5–10 km).

b. Occurrences of single- and multilayer hydrometeors

For the 778 352 and 749 037 profiles over the 14 months in eastern China and the Indian region, 80% and 70% are cloudy profiles, to which single-layer hydrometeors contribute 63% and 53%, respectively (Table 1). In both regions, multilayer hydrometeors are common, with double-layer hydrometeors accounting for about one-third of the total frequencies, and triple-layer hydrometeors contribute 7% in eastern China and 12% in the Indian region. Contribution from four- and five-layer hydrometeors is negligible (<3%).

The seasonal variations in the total occurrence frequency of hydrometeors exhibit distinguished features between the two regions (solid lines in Figs. 2a,b). The monthly occurrence frequencies are relatively constant among the seasons in eastern China, with a minimum of 64% in December 2006 and a maximum of 90% in June 2007. The hydrometeor amount varies significantly with season in the Indian monsoon region with maxima > 90% during the summer months and minima about 30%–40% during January–March 2007.

The seasonal features in the amounts of single- and multilayer hydrometeors also differ between the two regions (dashed lines in Figs. 2a,b). In eastern China, the occurrence frequency of single-layer hydrometeors is slightly larger from October 2006 to April 2007, while that of the multilayer is larger during the summer months. That is, the seasonal variations in the occurrence frequencies of the single-layer and the multilayer hydrometeors are somewhat in opposite phase, resulting in little change with season in the total hydrometeor amount. In the Indian region, the multilayer frequencies exhibit remarkable seasonal variation with a maximum during summer and minimum during winter, similar to that of the total frequency. The monthly occurrence frequency of single-hydrometeor layers changes little with season. Therefore, it is the seasonal variation in the multilayer hydrometeors that causes the pronounced change with season in the total hydrometeor amount.

Examination of the relative contributions to the total occurrence frequency by the single-, double-, triple-, and four-layer hydrometeors reveals both similarities and differences between the two regions. In both regions, single-layer hydrometeors are relatively more/less common during the winter/summer months, in contrast to multilayer hydrometeors. There are considerable contributions by double- and triple-layer hydrometeors, especially in the summer months, while the contribution by four- and five-layer hydrometeors (<4%) is negligible in both regions. The more frequent occurrences of multilayer hydrometeors during summer indicate more complicated cloud-layer structures associated with the Asian summer monsoon. The major differences between the two regions are as follows: In eastern China, single-layer hydrometeors contribute at least 50% to the total hydrometeor amount during all months. About 20%–40% and a few to 12% of the monthly total amounts are contributed by double- and triple-layer hydrometeors, respectively. In the Indian region, multilayer hydrometeors contribute about 60% to the total hydrometeor amounts during the summer months, while single-layer hydrometeors dominate the total amounts from October to May (relative contributions of 60%–90%).

c. Comparison with Y01 cloud amounts

Figure 3 demonstrates the seasonal variations in hydrometeor amounts based on the GEOPROF-lidar product and those derived from the ISCCP data (Y01). Despite the difference in cloud-type definitions between the two analyses (section 3), the two datasets reveal the same major seasonal features in not only the fraction of cloudy profiles (Figs. 3a and 3b) but also the amounts of the uppermost hydrometeor layers with high, mid-, and low tops (Figs. 3c–h). The differences in cloud amounts, which are to be discussed below, could be due to the difference in the time periods of the ISCCP dataset used by Y01 and the CloudSat/CALIPSO products utilized here, combined with interannual variations in the hydrometeor amounts. Moreover, the different cloud amounts could also attribute to the fact that CloudSat/CALIPSO only observes at 0130 and 1330 LST, while the ISCCP measurements cover the full diurnal cycle. The limited pixel numbers from the CloudSat/CALIPSO products may be another reason. Other

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**Table 1.** The numbers of all profiles, fractions of cloudy profiles, and the relative fractions of cloudy profiles that contain in the column single-, double-, triple-, and four-layer hydrometeors, respectively, in eastern China and the Indian monsoon region during July 2006–August 2007.

<table>
<thead>
<tr>
<th>Pixel type</th>
<th>All</th>
<th>Cloudy</th>
<th>One layer</th>
<th>Two layer</th>
<th>Three layer</th>
<th>Four layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern China</td>
<td>778 352</td>
<td>0.80</td>
<td>0.63</td>
<td>0.29</td>
<td>0.07</td>
<td>0.01</td>
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<tr>
<td>Indian monsoon region</td>
<td>749 037</td>
<td>0.70</td>
<td>0.53</td>
<td>0.33</td>
<td>0.12</td>
<td>0.02</td>
</tr>
</tbody>
</table>
possible causes include the limitations associated with
the ISCCP algorithms (e.g., Liao et al. 1995) and other
uncertainties related to the GEOPROF-lidar product.

Compared to the total cloud amounts obtained by
Y01, the monthly hydrometeor amounts (i.e., fractions
of cloudy profiles) obtained here are about 10% larger
for most months (Figs. 3a and 3b). On the one hand,
this discrepancy is likely caused by the inability/diffi-
culty of the ISCCP cloud-detection algorithm to detect
optically thin clouds (Rossow and Garder 1993). On
the other hand, the discrepancy may also be contrib-
uted by precipitation that could be detected by the
CPR but might not be considered in the ISCCP data.
These reasons could also cause the smaller occurrence
frequencies revealed by the ISCCP dataset for low-
topped clouds (Figs. 3g and 3h), with discrepancies
being larger during summer in both regions. The two
datasets reach a better agreement for the amounts of
the high- and mid-topped hydrometeors (Figs. 3c–f).
Furthermore, an overestimate in the ISCCP midtop
cloud amount usually corresponds to an underestimate
in its high-top cloud amount, reflecting the difficulty
with the ISCCP algorithms to correctly locate the
cloud tops.

5. Thickness, top, and base of hydrometeor layers

The top height ($H_{ct}$), base height ($H_{cb}$), and thickness
($\Delta H$) of hydrometeor layers are important character-
istics, as they significantly impact radiation budget at the
top of the atmosphere and the surface. In this section,
joint frequency distributions of $H_{cb}$ versus $H_{ct}$ during
each season are presented for all hydrometeors as well
as the single- and multilayer hydrometeors, respect-
ively, for the two regions (Figs. 4 and 5) to investigate
seasonal features of these quantities. The mean and
median values of $\Delta H$ are provided in Table 2 in which
we find a mean (median) layer thickness of approxi-
mately 2.5 km (1.4 km) in eastern China and 3.1 km (1.7
km) in the Indian region. The means and medians
decrease with the number of hydrometeor layers co-
occuring in the column in both regions.

A few similar features can be seen between Figs. 4
and 5. The distributions for both single- and multilayer
hydrometeors display peaks near the lower-left area
during all seasons, suggesting that geometrically thin
low-level hydrometeors occur frequently all year, in
particular during winter. Compared to the single-layer
distributions, the multilayer distributions show more
populations along the major diagonal, indicating geo-
metrically thin hydrometeors occurring at various alti-
tudes in the troposphere. During summer a peak at tops
of 12–18 km and bases of 10–16 km is noticeable in the
single-layer distributions, caused by anvils and cirrus
clouds. Also noticeable is a peak at the same top range
but based near the surface, suggesting thick hydrome-
teor layers associated with deep convection. Most of
the thick hydrometeor layers consist of contiguous

FIG. 2. Monthly-mean occurrence frequencies of all hydrometeor layers and single-, double-, triple-, and four-layer
hydrometeors, respectively, in (a) eastern China and (b) the Indian monsoon region during the period from July 2006
to August 2007.
sublayers, as suggested by the modes at $H_{ct}$ of $\sim 16\ km$ and $H_{cb}$ of $1–2\ km$ in the single-layer distributions (Figs. 4f and 5f,g) that are not shown in the corresponding multilayer distributions (Figs. 4j and 5j,k).

A few differences between the two regions are revealed by comparing Fig. 4 with Fig. 5. Most importantly, a bimodal feature is obvious in Figs. 5a–d with the modes located at the low and upper ends of the major diagonal. These suggest that geometrically thin high- and low-level hydrometeor layers are common in the Indian region with fewer mid-level hydrometeors. Eastern China mainly has geometrically thin hydrometeor layers at mid- and low levels, except during summer. Moreover, there are relatively more occurrences of thick hydrometeor layers (thicker than 10 km) in the Indian region during summer and autumn, confirming that the summer convection is more intense and deeper in the Indian region than in eastern China.

![Fig. 3. Monthly-mean occurrence frequencies of (a), (b) cloudy profiles; (c), (d) high-top hydrometeors; (e), (f) midtop hydrometeors; and (g), (h) low-top hydrometeors in (left column) eastern China and (right column) the Indian monsoon region during the period from July 2006 to August 2007 based on the GEOPROF-lidar data (solid lines). Also shown are the statistics of monthly cloud amounts from Y01 based on the ISCCP dataset (dashed lines).]
6. Radar reflectivity factor

a. CFADs of dBZ for all cloudy profiles

The normalized CFADs of dBZ for all cloudy profiles during each season (Fig. 6) differ remarkably between the two regions. Eastern China patterns exhibit obvious seasonal variations with the summer and winter patterns differing most significantly (Figs. 6a–d). Compared to other seasons, the shades (larger occurrence frequencies) extend to higher altitudes and cover a narrower dBZ range at the same height during summer. Low-level clouds (below 4 or 5 km)—which are common during autumn, winter, and spring in eastern China—have dBZ values covering a wide range, indicating that the radii of particles in the interior of the clouds vary significantly among the cloud elements. During all seasons the hydrometeors have double dBZ minima with frequency of high reflectivity increasing with decreasing altitudes. The dBZ maximum at 4–8 km from spring to autumn is likely due to large aggregates.

Compared to eastern China, the Indian region is more dominated by ice clouds with small dBZ values, suggesting small ice crystals (Figs. 6e–h). The dBZ distributions appear quite similar between summer and autumn and most distinguished in winter. From spring to autumn, a mode is shown at 10–14 km within the smaller dBZ bins, indicating ice clouds consisting of small ice crystals. The occurrences of large dBZ increase from cloud top with decreasing height reaching a maximum at 5–6 km, reflecting large ice crystals (snowflakes) formed by accretion and aggregation in the lower part of ice cloud layers. During winter most Indian clouds are located high (10–14 km) with dBZ values being small (<10) (Fig. 6h), in contrast to eastern China where very few high-level clouds occur and low-level clouds dominate (Fig. 6d). There are shallow clouds located below 4 or 5 km with dBZ covering a wide range, although the relative amount of these clouds is much smaller than that during the eastern China winter season.

b. CFADs of dBZ for deep convective profiles and anvils

Figure 7 shows the normalized CFADs for the summer deep convective profiles (Figs. 7a,b) and anvils
(Figs. 7c,d) that are constructed as described in section 3. The distributions are nearly identical between the two regions for both deep convection and anvils except that the Indian region convection is deeper.

The deep convection CFADs show two modes. One is located at 4–5 km with dBZ between 10 and 15, while the other at ~3 km with dBZ between 5 and 10. Vertical variations in dBZ tend to be opposite at heights above and below the freezing level (4 km), indicating distinct microphysical processes. The high frequencies of dBZ > 10 at 4–8 km indicate large ice-phase hydrometeors formed by accretion and aggregation. The high frequencies of dBZ between 5 and 10 at 2–4 km are probably due to large rain drops formed through melting of ice-phase particles (snowflake and graupel). The double dBZ minima at 12–14 km and 2 km, respectively, indicate small ice crystals near the top of the convective system and attenuation due to raindrops at the low altitudes. The CFADs distribute quite wide at each altitude, suggesting co-occurrence of small and large particles at the same height.

The anvil CFADs display a single maximum at ~12 km within the smallest dBZ bins (i.e., dBZ < −15), indicating that the anvils mainly consist of small ice crystals. The average size of ice crystals increases with decreasing height resulting from accretion and aggregation processes. The anvil tops reach about the same height in the two regions, although the convection is deeper and stronger in the Indian region.

7. Summary and conclusions

Mainly impacted by the Asian summer monsoon, the seasonal cycles of surface precipitation rates in eastern China and the Indian monsoon region are in phase (e.g.,

<table>
<thead>
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<th>Pixel type</th>
<th>Cloudy</th>
<th>One layer</th>
<th>Two layer</th>
<th>Three layer</th>
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</thead>
<tbody>
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<tr>
<td>Indian monsoon region</td>
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<td>1.8</td>
<td>1.4</td>
<td>1.1</td>
</tr>
<tr>
<td>Indian monsoon region</td>
<td>1.7</td>
<td>2.1</td>
<td>1.8</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Wang and LinHo (2002). However, previous analyses of the ISCCP and ERBE data by Yu et al. (Y01) revealed that the cloud fractions and cloud radiative forcings differ significantly between the two regions, suggesting that the vertical distributions and internal structures of hydrometeors could be different between the two regions. Moreover, correct simulation of hydrometeor occurrence and vertical structure (location and particle size) is critical for GCMs to make accurate climate projections, as the hydrometeor characteristics affect both radiation and microphysical processes and thus climate.

Fig. 6. Normalized CFADs of dBZ for all cloudy profiles in (left) eastern China and (right) the Indian monsoon region during (top) spring to (bottom) winter. The bin size is 10 dBZ in the horizontal and 1 km in the vertical. The long dashed and solid lines represent contours of 0.001 and 0.01, respectively.
The present study uses two standard CloudSat products, GEOPROF and GEOPROF-lidar, to investigate the seasonal variations in the occurrence frequency, vertical distribution, and dBZ characteristics of hydrometeor layers in eastern China (20°–35°N, 102.5°–122.5°E) and the Indian monsoon region (10°–25°N, 70°–90°E) during the period from July 2006 to August 2007. In total, 1,527,389 profiles have been analyzed.

Averaged over the 14 months, the occurrence frequency of hydrometeors is 80% in eastern China and 70% in the Indian region, to which the single-layer hydrometeors contribute 63% and 53%, respectively. Most of the multilayer hydrometeors have double or triple layers co-occurring in the column (relative contribution > 97%). The seasonal variations in the occurrence frequencies of single-layer, multilayer, and all hydrometeors differ significantly between the two regions. The total hydrometeor occurrence frequencies (HOF) exhibit remarkable seasonal variations in the Indian region, being nearly overcast in summer and decreasing to 30%–40% during winter, owing to significant changes in the multilayer hydrometeor occurrences with season. In contrast, the total HOF in eastern China remains quite constant with season, resulting from the nearly opposite seasonal features in the occurrences of single- and multilayer hydrometeors.

The cloud amount statistics obtained by Y01 based on spaceborne passive sensors reveal the same major seasonal features as those obtained using the GEOPROF-lidar product. However, the HOF was underestimated by about 10% in both regions by the ISCCP dataset, mostly because of the underestimate in the occurrence frequencies of low-topped hydrometeors, probably due to the inability to detect optically thin hydrometeors by the ISCCP algorithms as well as the inclusion of some precipitation by the GEOPROF-lidar product.

There are more (less) hydrometeors occurring at upper (mid plus low) troposphere in the Indian region than in eastern China during nearly all seasons. The hydrometeor layers are geometrically thin in both regions with median thicknesses of 1.4 km (China) and 1.7 km (Indian). The thickest hydrometeors in both regions consist of contiguous subhydrometeor layers occurring most frequently during summer and seldom in winter as expected.

Moreover, low-level cloud layers are not uncommon throughout the year in the two regions, being the major

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**FIG. 7.** Normalized CFADs of dBZ for the (a), (b) convective profiles and (c), (d) anvils in (left) eastern China and (right) the Indian monsoon region during the summer months. The bin size is 5 dBZ in the horizontal and 1 km in the vertical.
cloud type during the eastern China winter. Yu et al. (2004) provided evidence showing that these clouds are generated and maintained by the frictional and blocking effects of the Tibetan Plateau, located to the west of eastern China. They found that the plateau slows the westerly flow at midlevel, inducing downstream midlevel divergence; meanwhile it forces the low-level flows to converge downstream, generating sustained large-scale lifting and stable stratification that maintain the stratus clouds.

Impacts of the Asian summer monsoon on hydrometeors in the two analysis regions are demonstrated by the sharp increase in the amount of hydrometeors in the upper troposphere and more occurrences of thick hydrometeor layers (geometric thickness of ~15 km) during summer. Compared to eastern China, there is a larger amount of deep convection and anvils and the convection is more intense and deeper in the Indian region, consistent with the classification of the Indian summer monsoon as a tropical monsoon and the eastern Asian summer monsoon as a subtropical monsoon (e.g., Wang and LinHo 2002).

The normalized CFADs of dBZ for all cloud profiles demonstrate that the Indian hydrometeors are dominated by ice-phase clouds containing small ice crystals, whereas the eastern China hydrometeors are located lower and distributed more evenly in the dBZ–altitude phase space, suggesting more condensed water content in the column. In both regions, larger ice particles occur more frequently at lower altitudes (4–8 km) because of the aggregation and accretion processes. The low-level cloud layers below 4–5 km in eastern China especially during winter contain mainly small particles, although the range of particle size is wide. The small particle size combined with a large amount of water mass suggests a large cloud optical depth, consistent with Yu et al. (2004), who found that these stratus clouds produce extremely strong cloud radiative forcing at the top of the atmosphere, which fundamentally influences the local energy balance and climate change. Therefore, representation of these clouds in GCMs could significantly impact the accuracy of the model climate projection.

While the occurrences of deep convection and anvils are more frequent in the Indian region than in eastern China during summer, the normalized CFADs of dBZ for the deep convective profiles and anvils, respectively, are nearly identical between the two regions except for the higher convection tops in the Indian region. These may suggest that large-scale processes and local processes play different roles in controlling the occurrence and internal structure of the hydrometeors. The occurrences of deep convection are mainly controlled by large-scale conditions that differ significantly between the two regions (tropics versus subtropics) and vary with season in a region. The amount of anvils could be controlled by both the detrainment from deep convection (and hence the large-scale conditions) and the interactions among various processes at smaller scales (such as radiation, turbulence, and microphysics). However, the internal structures of the deep convective hydrometeors and anvils are mostly constrained by the microphysical processes, which statistically act in similar ways in the two regions.

Results from this study are potentially valuable to validate GCM simulations of the Asian hydrometeors and pinpoint weaknesses in the model parameterizations. For that purpose, one may use simulators that can take model output and produce synthetic radar and lidar measurements. The major procedures of such simulators can be summarized as two steps: First, create a synthetic subgrid-scale hydrometeor (cloud and precipitation) field from the model’s large-scale hydrometeor variables (cloud water/ice mixing ratio, cloud fraction, precipitation fluxes) based on the model’s assumptions about subgrid-scale cloud/precipitation variability and overlap (e.g., Klein and Jakob 1999; Luo et al. 2005). Second, calculate dBZ from the synthetic hydrometeor field based on the model assumptions about hydrometeor size distributions (e.g., Haynes et al. 2007). Then the methods to analyze the CloudSat/CALIPSO product can be applied to the output from the simulators.

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