Observational Characteristics of Cloud Vertical Profiles over the Continent of East Asia from the CloudSat Data

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ABSTRACT

The CloudSat satellite data from June 2006 to April 2011 are used to investigate the characteristics of cloud vertical profiles over East Asia (20°–50°N, 80°–120°E), with particular emphasis on the profiles of precipitative clouds in comparison with those of nonprecipitative clouds, as well as the seasonal variations of these profiles. There are some obvious differences between the precipitative and nonprecipitative cloud profiles. Generally, precipitative clouds mainly locate below 8 km with radar reflectivity in the range of –20 to 15 dBZ and maximum values appearing within 2–4-km height, and the clouds usually reach the ground; while nonprecipitative clouds locate in the layers of 4–12 km with radar reflectivity between –28 and 0 dBZ and maximum values within 8–10-km height. There are also some differences among the liquid precipitative, solid precipitative, and possible drizzle precipitative cloud profiles. In precipitative clouds, radar reflectivity increases rapidly from 11 to 7 km in vertical, implying that condensation and collision-coalescence processes play a crucial role in the formation of large-size drops. The frequency distribution of temperature at –15℃ is consistent with the highest frequency of radar reflectivity in solid precipitative clouds, which suggests that the temperatures near –15℃ are conductive to deposition and accretion processes. The vertical profiles of liquid precipitative clouds show almost the same distributions in spring, summer, and autumn but with differences in winter at mainly lower levels. In contrast, the vertical profiles of solid precipitative clouds change from spring to winter with an alternate double and single high-frequency core, which is consistent with variations of the frequency distribution of temperature at –15℃. The vertical profiles of nonprecipitative clouds show a little change with season. The observations also show that the precipitation events over East Asia are mostly related to deep convective clouds and nimbostratus clouds. These results are expected to be useful for evaluation of weather and climate models and for improvement of microphysical parameterizations in numerical models.

Key words: CloudSat, cloud vertical profile, precipitative and nonprecipitative clouds, cloud radar reflectivity, frequency distribution


1. Introduction

The vertical structure of a cloud reflects the thermal and dynamical processes as well as microphysical processes in the cloud. Radiation and latent heating have strong influences on the large-scale atmospheric circulation (Randall et al., 1989; Slingo and Slingo, 1991; Wang and Rossow, 1998; Wang, 2011). Vertical variations in cloud fraction and cloud optical thickness affect microphysical processes in clouds, thereby influencing the occurrence and intensity of precipitation (Jakob and Klein, 1999). Therefore, knowledge on the cloud droplet vertical profile is essential for understanding precipitation (Rosenfeld, 2000; Rosenfeld...
In many single-moment models, the cloud droplet concentration ($N_c$) is set to a constant (e.g., Lin et al., 1983; Morrison et al., 2009; Lin and Colle, 2011). However, observations show that $N_c$ varies greatly with altitude (e.g., Wu, 1987; Chen et al., 1999; Wang et al., 2005; Li, 2006). Additionally, knowledge of the cloud hydrometeor vertical profiles is important for data assimilation. Satellite and radar data have been widely used in the initialization of numerical models (e.g., Xue et al., 2003; Barker et al., 2004; Liu et al., 2008). However, cloud hydrometeor data cannot be acquired directly from satellite and radar observations, and only vertically integrated and effective cloud properties are inferable based on the measurement data. It is impossible to obtain the vertical distributions of hydrometeors (i.e., cloud droplet, raindrop, ice, snow, graupel, and hail) from the conventional soundings. As a result, knowledge of the cloud vertical property is inadequate though it is important to the understanding of cloud physics, large-scale circulation, and data assimilation.

Some methods have been applied to retrieving cloud vertical properties (e.g., Poore et al., 1995; Gultepe and Isaac, 1997; Wang and Sassen, 2001; Korolev et al., 2007; Vanderlei Martins et al., 2007; Carey et al., 2008). Although good agreements have been achieved from these studies, these cloud profiles are limited in their temporal and spatial extent. It is hard to learn cloud vertical properties generally. CloudSat, part of the A-Train constellation of satellites, provides a detailed view of three-dimensional structure of cloud and precipitation from space. CloudSat has mounted a 94-GHz, nadir-pointing, cloud profiling radar (CPR), and provides the profiles with a vertical resolution of 500 m and a footprint of approximately 1.4 km. CloudSat flies one orbit approximately every 99 min and repeats the same ground track every 16 days. CloudSat products have 125 vertical bins, with each bin approximately 240-m thick. Since launched in April 2006, CloudSat has been creating a continually growing database. The database is useful for a wide range of meteorological applications, including evaluation of numerical prediction models and improvement of cloud microphysical schemes.

Many consistency analyses have been made and it is pointed out that CloudSat products perform well. Paquita and Brian (2008) made a comparison between ship-based (35 GHz) and space-based (94 GHz) cloud radar data, and showed that CloudSat is better than the ship-based radar at detecting the upper-tropospheric clouds with reflectivity greater than −30 dBZ, but it performs more limited detection of clouds with reflectivity less than −30 dBZ. Protat et al. (2009) conducted a quantitative assessment of CloudSat reflectivity and basic ice cloud properties from both airborne and ground-based observations. Their results showed that there was a little weighted-mean difference of reflectivity between CloudSat data and ground-based observations. The comparison between CloudSat data and in-situ measurements taken by Baker et al. (2008) and Austin et al. (2009) also showed that CloudSat products performed well. Additionally, many studies on cloud microphysics and verification of weather and climate models have been carried out based on the CloudSat products (e.g., Bodas-Salcedo et al., 2008; Stephens et al., 2008; Waliser et al., 2010).

A number of studies have also been made for cloud and precipitation microphysical properties over East Asia. For instance, Liu and Fu (2001) analyzed the characteristics of tropical precipitation vertical profiles observed by the Tropical Rainfall Measuring Mission (TRMM) satellite. Fu et al. (2003) proposed that dominant stratiform rain events contribute to 50% of the total precipitation with an approximate 83.7% area fraction over East Asia, and deep convective rains contribute to 48% of the total precipitation with a 13.7% area fraction. Yin et al. (2011) summarized the microphysical particle concentrations and size distributions based on long-term in-situ observation data. In addition, Luo et al. (2009) compared occurrences and vertical structures of hydrometeors between eastern China and the Indian monsoon region using the CloudSat and CALIPSO data, and Wang et al. (2011) analyzed the macro-structure of clouds over China and its neighborhood based on the CloudSat data. However, there have been few investigations into the vertical profile of cloud microphysical properties over East Asia.

The main objective of this study is to advance our
understanding of cloud vertical profile characteristics over the continent of East Asia based on the CloudSat data, with particular emphasis on the vertical cloud profiles. It is expected that these results will be useful for configuration of future microphysical parameterizations and they can also provide a basis for weather and climate model verification. A general description of the data and method is given in Section 2. The analytical results are shown in Sections 3–5. Section 6 provides conclusions.

2. Data and methods

2.1 Data description

Three kinds of publicly available CloudSat standard data, i.e., level 2B GEOPROF, 2B CLDCLASS, and ECMWF-AUX data, during the period from June 2006 to April 2011, are used in this study. The 2B GEOPROF product contains significant radar reflectivity factor and provides an estimate of the radar reflectivity factor known as the cloud mask. A value of the cloud mask in the range of 20–40 indicates that reliable hydrometeors are detected. Note that land surface has a strong influence on radar reflectivity of near-surface layer. In view of this, the data points below 0.5 km are discarded.

The 2B CLDCLASS data contain cloud types, precipitation flag, and the others (Wang and Sassen, 2001). The 2B CLDCLASS product uses the 2B GEOPROF product as a quality level to determine cloud types. The clouds with a confidence of the cloud mask greater than 20 are classified into Altocumulus (Ac), Deep convective (Dc), Cumulus (Cu), Nimbostratus (Ns), Stratocumulus (Sc), and Stratus (St). It should be noted here that, by precipitation, we mean precipitation particles formed in clouds rather than the real precipitation reaching the ground. According to the occurrence of precipitation, the clouds are divided into precipitative clouds and nonprecipitative clouds. The phase of precipitation can be approximately discriminated from temperature profile and the occurrence of bright band in radar signals. If the bright band is identified and/or the temperature near the ground surface is at least warmer than 2 degrees, the precipitation is regarded as liquid. Otherwise, the precipitation is labeled as solid precipitation. After precipitation identification, –18 dBZ is selected to detect possible drizzle occurrence based on the maximum radar reflectivity for boundary layer clouds.

The ECMWF-AUX dataset is an intermediate product that contains the set of the ancillary ECMWF state variable data interpolated to the CloudSat track. The input data are obtained from the AN-ECMWF dataset provided by the European Center for Medium-Range Weather Forecasts (ECMWF). Fields of surface pressure, temperature, specific humidity, zonal velocity, meridional velocity, vertical velocity, and ozone on the CloudSat track are thus provided.

To reveal the details of East Asian cloud vertical structures, only the CloudSat profiles that have passed within the East Asian region are selected. The geographical coverage of East Asia (20°–50°N, 80°–140°E) is shown in Fig. 1. In view of that many studies have pointed out the difference of cloud properties between oceans and continents (e.g., Squires, 1958; Miles et al., 2000), only the clouds over land are further analyzed in this paper.

2.2 Methods

The flowchart of the CloudSat data processing is displayed in Fig. 2. Firstly, any CloudSat profile located in the geographical region shown in Fig. 1 is selected. Secondly, each data point is checked to determine whether it is cloudy or not. If it is cloudy, the data point is further analyzed to find whether precipitation is formed in the cloud or not. Thirdly, the precipitative clouds are classified into liquid precipitative cloud, solid precipitative cloud, and possible driz-
The precipitative cloud. Additionally, precipitation is also distinguished in terms of cloud types.

Yuter and Houze (1995) employed a statistical technique based on Contoured Frequency by Altitude Diagram (CFAD), to display the statistical distribution of the storm properties for the first time. However, the CFAD method has a side effect of increasing the percentages at the altitudes where there are fewer data points. To overcome such a weakness, many studies (e.g., Fu et al., 2003; Luo et al., 2009; Yuan et al., 2011) suggested an improved statistical technique known as the Normalized Contoured Frequency by the Altitude Diagram (NCFAD). The improvement is that the frequency for each box is normalized to the total number of points in all level boxes in the altitude phase space.

The NCFAD, in this study, is constructed with height on the y-axis and radar reflectivity on the x-axis. Contours with colors filled describe the frequencies of radar reflectivity normalized by total numbers of cloud profiles. There are 125 levels at an interval of 0.24 km on y-axis. The values of radar reflectivity at an interval of 1 dBZ are labeled on x-axis. As for the frequency distribution of temperature as seen in the figures in this paper, the corresponding contours represent the frequencies of a chosen temperature (e.g., 0°C) normalized by total numbers of data points with the same value (as 0°C) at all levels. Note that the temperature within the range of 0±1.0°C is considered as 0°C due to the accuracy of the ECMWF-AUX data. The same is applied to the temperature of −15°C.

3. Cloud profile characteristics

Figure 3 plots the NCFADs for the precipitative clouds (Fig. 3a) and nonprecipitative clouds (Fig. 3b). The precipitative clouds have a maximum top of nearly 18 km, with the maximum values of radar reflectivity greater than 40 dBZ. Only a small part of precipitative clouds appears above the height of 12 km, and the most part of them concentrates on the levels between 1 and 9 km, with their radar reflectivity values in the range from −5 to 17 dBZ. The vertical distribution of maximum frequency represents the basic characteristics of the precipitative clouds profile. It is seen from Fig. 3a that the radar reflectivity shows a low value (~25 dBZ) above the height of 12 km. The radar reflectivity increases rapidly with the decreasing of height from 12 to 7 km, remains almost unchanged between 7 and 4 km, and decreases from 4 to 1 km. The statistical results agree well with previous studies, such as Donaldson (1961), Willis and Heymsfield (1989), Yuter and Houze (1995), Smedsmo et al. (2005), Xu et al. (2009), and others.
Fig. 3. Radar reflectivity distributions of (a) precipitative and (b) nonprecipitative clouds. The vertical axis represents height with intervals of 240 m, and the horizontal axis denotes radar reflectivity with intervals of 1 dBZ. Shaded areas indicate the percentage of the corresponding radar reflectivity at different heights to the overall radar reflectivity, and the thin line is the curve that connects the points of maximum frequency for each and every height.

The aforementioned profile suggests that the hydrometeor particle size increases rapidly downward from 12 to 7 km. The radar reflectivity reaches a maximum value near the height of 4 km and then drops down. This implies that the hydrometeor particles grow up when they fall downward, and cumulate around the height of 4 km due to some dynamical and microphysical processes. Generally, vertical velocity increases with the increasing of height and then decrease after it reaches the maximum at a certain height. Such a distribution of vertical velocity agrees well with the profile of the radar reflectivity.

For the nonprecipitative clouds, the radar reflectivity can scarcely reach the ground. The maximum top of the nonprecipitative clouds is 17 km, with a maximum value of radar reflectivity less than 20 dBZ. Most of the nonprecipitative clouds concentrate on the levels between 2 and 12 km, with the radar reflectivity in the range from –28 to 0 dBZ. The maximum frequency of the nonprecipitative clouds occurs at 7–9-km height, with the values of the radar reflectivity in the range from –26 to –24 dBZ.

Precipitative clouds can be divided into liquid precipitative cloud, solid precipitative cloud, and possible drizzle precipitative cloud according to the phase of precipitation. Figure 4 plots the NCFADs for the liquid and solid precipitative clouds. As can be seen, the pattern of NCFADs for the liquid precipitative clouds is very similar to that for the precipitative clouds, indicating that liquid precipitation is quite common over East Asia. The liquid precipitative clouds with radar reflectivity greater than 30 dBZ are located at the heights between 4 and 6 km. The maximum frequency of temperature at 0°C agrees well with the zone of larger radar reflectivity. This may indicate that melting plays an important role in the formation of “bright band”. Besides, the rapid increase of radar reflectivity from 11 to 4 km suggests that these heights are very beneficial to the growing of the particles.

The NCFADs for the solid precipitative clouds are shown in Fig. 4b. Obviously, different patterns can be found between solid precipitative clouds and liquid precipitative clouds. There are two levels of the highest probability for the occurrence of solid precipitative
clouds. The lower one locates at the level between 2 and 3.5 km with the radar reflectivity values in the range from –3 to 6 dBZ; and the other locates at the level between 6 and 7 km, with the radar reflectivity values in the range from –13 to –5 dBZ. The statistical results show that the frequency distribution of temperature at –15°C is in accordance with the distribution of radar reflectivity, suggesting that the probability for the occurrence of large particles is the highest if the temperature is near –15°C in the solid precipitative clouds. The results are consistent with previous studies, such as Hobbs et al. (1974) who studied cyclonic and orographical cloud systems over the Cascade Mts., Washington, and Rogers (1974) who studied orographical cloud systems over Elk Mt., Wyoming of the United States.

The possible drizzle precipitative clouds always occur below 7 km, and most of them concentrate at the levels between 1.5 and 4 km, with radar reflectivity ranging from –26 to –3 dBZ (Fig. 5). Most of drizzle precipitation originates from low clouds as seen in the conventional observations. It should be however noted that, based on the analyses of the CloudSat data, the drizzle precipitation is also able to generate from middle clouds, which might imply that the size of large cloud droplets decreases gradually due to evaporation.

Fig. 4. As in Fig. 3, but for (a) liquid precipitative clouds and (b) solid precipitative clouds. The solid lines are the curves of the maximum frequency, and the dashed lines are the frequency distribution of temperature at (a) 0°C and (b) –15°C. Tick marks for temperature frequency are given on the top of each panel.

Fig. 5. As in Fig. 3, but for possible drizzle precipitative clouds.
during their falling from the upper level to the ground. In sum, not only low clouds, but also middle clouds contribute to drizzle precipitation events. This means that the same type precipitation may originate from different types of clouds.

There are significant differences in vertical profiles of the liquid, solid, and possible drizzle precipitative clouds. The liquid precipitative clouds have the highest top and show the greatest radar reflectivity, compared with other types of clouds. There are two highest probability levels for the occurrence of the solid precipitative clouds, and most of the drizzle precipitation originates from low clouds. As far as East Asia is concerned, liquid precipitative clouds are the major precipitative clouds, followed by solid precipitative clouds.

4. Seasonal variations of the cloud vertical structure

4.1 Precipitative clouds

The seasonal variation of precipitative cloud vertical structure is clearly shown in distributions of the NCFADs in Fig. 6. The precipitative clouds have a maximum top higher than 17 km during spring–autumn, while below 14 km in winter. Besides, the pattern of the NCFADs shows a little difference from spring to autumn. In spring, the maximum top of the liquid precipitative clouds is the highest.
precipitative clouds reaches 18 km with the maximum values of radar reflectivity greater than 36 dBZ. Most of the precipitative clouds concentrate at the level between 1 and 8 km with the radar reflectivity from –10 to 15 dBZ. From the vertical distribution of maximum frequency, the radar reflectivity shows a little variation with a low value (about –25 dBZ) above 11 km. The radar reflectivity increases rapidly with the decreasing of height from 12 to 4 km, and shows a decreasing tendency from 4 to 1 km.

The pattern of the NCFADs for summer is very similar to that of the precipitative clouds in a full year, which means that the precipitative clouds in summer account largely for the precipitative clouds over East Asia. The pattern of the NCFADs for autumn shows a little difference, compared with that for spring. In winter, most of the precipitative clouds concentrate on levels below 8 km (especially below 4 km) with radar reflectivity from –10 to 15 dBZ. Note that the evolution of the liquid precipitative clouds is similar to that of the precipitative clouds.

Figure 7 plots the NCFADs for the seasonal variation of the solid precipitative cloud vertical structure. As can be seen, the highest probability levels for the occurrence of solid precipitation clouds vary considerably from season to season. There are two highest probability levels in spring, and the upper one is stronger than the lower one. In summer, there is one

![Figure 7](image-url)
highest probability level, which locates near 7 km. The pattern of the NCFADs in autumn is very similar to that in spring. In winter, there is only one highest probability level below 4 km.

There is no obvious seasonal variation of the NCFADs for the possible drizzle precipitation clouds. The patterns of NCFADs in different seasons are similar to that in a whole year shown in Fig. 5. In general, there appears a highest probability level between 1.4 and 2.6 km in both spring and winter, but the highest probability level is no obvious or almost disappears in summer and autumn.

### 4.2 Nonprecipitative clouds

The seasonal variation of the nonprecipitative cloud vertical structure is shown in distributions of the NCFADs in Fig. 8. It is seen that the pattern of the NCFADs is similar to each other in different seasons with a highest probability in all the seasons. However, the highest probability located within 6.5–9 km is the strongest in winter and weakest in summer. The highest probabilities locate at 9 and 7 km in winter and autumn, respectively. In brief, the vertical structure of the nonprecipitative clouds shows only a slight

![Fig. 8](image-url)
change with season, in spite of having a different radar reflectivity core in different seasons.

5. Vertical properties of dominant precipitative clouds

The statistics of the contribution of different types of clouds to the formation of precipitation is given in Table 1, which shows the cloud types, data points, and their percentages in the total. The statistical results show that the Dc clouds contribute the most (58.41%) to rain events, and the Ns is the second most contributor (29.51%), followed by the Cu, Sc, and Ac. The St scarcely causes precipitation events. It is seen from Table 1 that the Dc, Ns, Cu, and Sc contribute to more than 99% of the rain events over East Asia.

Figure 9 plots the NCFADs for Dc, Ns, Cu, and Sc. Obviously, different patterns can be found by com-

<table>
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<th>Cloud type</th>
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<th>Sc</th>
<th>Ac</th>
<th>Cu</th>
<th>Dc</th>
<th>Total</th>
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<td>187909</td>
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<td>0.83</td>
<td>7.21</td>
<td>58.41</td>
<td>100.00</td>
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</table>

Fig. 9. As in Fig. 3, but for the precipitative clouds of (a) Dc, (b) Ns, (c) Cu, and (d) Sc.
paring each other. The pattern of the NCFAD for Dc looks like a columnar, which may be associated with strong updrafts in deep convective clouds. The Dc clouds have a maximum top of 17 km, with radar reflectivity less than 20 dBZ. Most of the Dc clouds concentrate on the levels below 10 km, with radar reflectivity from −5 to 15 dBZ. From the distribution of maximum frequency, the radar reflectivity increases rapidly with the decreasing of height from 15 to 7 km, remains almost unchanged between 7 and 4 km, and decreases from 4 to 1 km. The Ns clouds have a maximum top of 16 km, and most of the Ns clouds concentrate on the levels between 1 and 8 km, with radar reflectivity from −10 to 15 dBZ. The maximum occurrence frequency of the Ns clouds locates at the height of 3 km, with the radar reflectivity values from −10 to 15 dBZ. The Cu clouds can reach the topmost height of 15 km, with the maximum values of radar reflectivity less than 20 dBZ. Most of the Cu clouds concentrate on the levels below 2 km, with radar reflectivity from −10 to 16 dBZ. The Sc clouds concentrate below 10 km, with a highest probability between 2 and 12 km and with radar reflectivity from −26 to 10 dBZ.

In summary, there are differences among the vertical structures of the Dc, Ns, Cu, and Sc clouds. The radar reflectivity of the Dc clouds increases rapidly with the decreasing of height from 15 to 7 km, remains almost unchanged between 7 and 4 km, and decreases from 4 to 1 km. However, radar reflectivity almost keeps unchanged at all levels in the nonprecipitative clouds.

6. Concluding remarks

In this study, we analyzed the cloud vertical profiles and their seasonal variations in the region. The results are as follows.

1. The precipitative clouds over East Asia always reach the ground while the nonprecipitative clouds scarcely do. Based on the distribution of maximum frequency of radar reflectivity in the precipitative clouds, radar reflectivity increases rapidly with the decreasing of height from 12 to 7 km, remains almost unchanged between 7 and 4 km, and decreases from 4 to 1 km. However, radar reflectivity almost keeps unchanged at all levels in the nonprecipitative clouds.

2. Radar reflectivity of the liquid precipitative clouds increases rapidly with the decreasing of height from 12 to 7 km. This indicates that hydrometeor particles might grow up potentially by collection, riming, and aggregation processes when they fall down. Liquid precipitations are quite common over East Asia.

3. The frequency distribution of temperature at −15°C is in accordance with the distribution of radar reflectivity in the solid precipitative clouds, and the probability for the occurrence of large particles is the highest at the temperature near −15°C.

4. The vertical distributions of precipitative clouds show little difference from spring to autumn, but different vertical distribution appears in winter at mainly the lower levels. The vertical distributions of solid precipitative clouds change from season to season with an alternate double and single high-frequency core, which is consistent with the variation of the frequency distribution of temperature at −15°C. The vertical distributions of nonprecipitative clouds barely change with season.

5. The deep convective (Dc) clouds contribute the most (58.41%) to the rain events, and the Ns is the second most contributor (29.51%), followed orderly by the Cu, Sc, and Ac. The St scarcely causes precipitation events.

This study concerns mainly the vertical distribution characteristics of the clouds over East Asia, which will help us further understand the cloud-precipitation processes over this region. Although some case studies such as Botton (1960), Donaldson (1961), Engholm and Troxel (1990), Yuter and Houze (1995), Smedsmo et al. (2005), and others have proposed part of the
same conclusions, the results established in the present study are more reliable and novel since they are based on a great deal of the CloudSat data. The results, in this study, may be helpful for evaluating the physical processes and hydrometeor fields simulated by a microphysical parameterization and for improving parameterization schemes in numerical models. In addition, the results might also be conductive to deriving appropriate retrieval algorithms for the remote sensing observations and weather modification.

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