Analysis on Evolution Characteristics of Hydrometeors in South China Based on Lagrange Tracking Method

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Abstract: To reveal the microphysical process of clouds inside a rain cluster and identify the causes of changes in water resources in the air in South China, rain cluster areas with the radar reflectivity factor higher than 40dBZ in a heavy precipitation process in South China were defined as convective cloud cores, and areas with the factor greater than 20dBZ and less than 40dBZ as stratiform clouds around cores with Lagrange tracking method based on S-band dual-polarization radar data. An analysis was conducted on the evolution law of the types of hydrometeor particles and variation characteristics of the raindrop size spectrum in the two areas as well as their differences. The results showed that convective cloud cores and surrounding stratiform clouds were composed of large and sparse raindrops at the early stage of development; the particle crushing process mainly occurred inside stratiform clouds at the mature stage, and the collision-coalescence process mainly occurred at the attenuation stage. Stratiform clouds showed a process of increase in the density of graupel particles at the stage of precipitation enhancement, but the density of graupel particles in convective cores did not change significantly; high- and low-density graupel particles in convective cores had a higher frequency of occurrence than those in stratiform clouds.

1. Introduction

South China, located in the subtropical and tropical monsoon climate zone and rich in water resources in the air [1], is an area with the longest flood season in China and frequent flood disasters. To reduce economic losses caused by heavy precipitation, it is necessary to have a deeper understanding of the physical mechanism of strong convective precipitation in South China. The microphysical characteristics of clouds reflect the interaction between their dynamics and microphysics. There are differences in the internal microphysical process between convective clouds and stratiform clouds in different precipitation types [2-4]. The understanding of the internal microphysical process of convective clouds and stratiform clouds, especially the evolution characteristics and differences of hydrometeors, will help to enhance the understanding of the physical mechanism of cloud precipitation and deeply understand the distribution of water resources in the air.

The evolution process of hydrometeors includes the process of transformation among different types of hydrometeor particles such as high- and low-density graupel particles as well as the process of change in the size and number concentration of hydrometeor particles. Due to strong vertical ascending motion in strong convection, clouds can often develop to above the 0°C layer, resulting in a complex ice phase process. Ice crystals can collide and coalesce to form snow or break into smaller crystals. They can develop into graupel particles if there is supercooled water [5-7]. We have inadequate
understanding of the microphysical structure of clouds in the precipitation process due to difficulties in observing their microphysical quantities. In addition, there are changes in raindrop number concentration and particle size during the occurrence and development of precipitation. In different cloud systems, the increase of precipitation intensity of convective clouds is accompanied by the increase of size and number concentration of precipitation particles, while that of precipitation intensity of stratiform clouds is mainly due to the increase of number concentration of large particles [8]. There is still no clear answer to how raindrops in convective cloud cores and their surrounding stratiform clouds are distributed and what differences there are in evolution characteristics.

S-band dual-polarization radars have obvious advantages in the observation of heavy precipitation, which can identify the scattering properties of different types of hydrometeor particles and thus deduce them by inversion. Previous studies based on radar data were dominated by the Eulerian viewpoint [9-11] which focused on some fixed points in space, i.e. observing the evolution of convective rain clusters at fixed points. However, methods based on the Lagrangian viewpoint are more appropriate if we want to observe the complete life cycle of convective rain clusters. The Lagrangian viewpoint focuses on individual convective rain clusters, identifying the evolution of each microphysical quantity in the whole life cycle of rain clusters through studies on their motion trail [12-13]. This paper analyzes the evolution law of precipitation particle types and variations in characteristics of the raindrop size spectrum in a strong precipitation process in South China based on Lagrange tracking method, mainly using S-band dual-polarization radar data, and provides scientific basis for our understanding of the causes of variations in water resources in the air in South China and more reasonable use of clean energy such as water resources.

2. Data and method

2.1. Data

The radar data used in the analysis was composed of the data from 11 S-band dual-polarization radars subject to quality control in South China in the period from 1600UTC on August 29, 2018 to 1554UTC on August 30, 2018 at 6min resolution; at 20°N~26°N and 108°E~118°E horizontally at 0.01°×0.01° resolution; and at 1~20km (20 layers) vertically at 1km resolution. Data variables included the radar reflectivity factor (ZH), differential reflectivity factor (ZDR), propagation specific differential phase shift (KDP) and zero lag correlation coefficient (ρHV) of source data as well as five physical quantities obtained from basic radar data inversion, including the precipitation particle type, rainfall rate (rr), mass median particle size (Dm), standardized intercept parameter (Nw) and liquid water content (LWC). The data was mainly processed with reference to the method of Huang, et al. [14] The method of Brandes, et al. [15] was referred to for radar inversion. See Song et al. [16] for inversion quality descriptions.

2.2. Lagrange tracking method

The precipitation system was tracked mainly with the method of Moseley et al. [17], iterative rain cell tracking (IRT). In the method, the radar reflectivity factor is a physical quantity used to identify targets in this paper. As the S-band radar echo is sensitive to precipitation particles, the location where the echo appears is the rainfall area. The continuum of the identified radar reflectivity factor is called a rain cluster. For rain clusters with a large area, the IRT algorithm judges their motion trail and speed based on their overlap at moments before and after. For those with a small area and unable to show an overlapping effect, the algorithm judges the same based on the iterative results of background circulation velocity and the movement speed of large rain clusters. In this paper, the radar reflectivity factors recognized by the algorithm are 20dBZ and 40dBZ, respectively, and the minimum area of recognition is 100km². It is stipulated that the area with the radar reflectivity factor greater than 40dBZ and an area greater than 100km² is the convective cloud core and the surrounding area with the factor greater than 20dBZ and less than 40dBZ is stratiform clouds around the core. When tracking rain clusters through the radar reflectivity factor, the algorithm can get recognition results including the
duration of rain clusters, their areas at each time level and the maximum, minimum and mean of the radar reflectivity factor in the recognition area. Besides, the algorithm can also calculate the maximum, minimum and mean of other physical quantities in corresponding rain clusters such as the frequency of occurrence of hydrometeor particle types, rainfall rate (rr) and mass median particle size (Dm), standardized intercept parameter (Nw) and liquid water content (LWC) which are also microphysical parameters of clouds mainly analyzed hereafter.

3. Analysis on rain cluster tracking and recognition results
According to the setting of recognition parameters described above, rain clusters in a precipitation process in August 2018 were tracked and recognized, and one of the rain clusters was selected as the target cluster for analyzing the evolution of microphysical quantities of clouds (Figure 1a). Each rain cluster had an independent duration expressed by the number of time steps each of which was 6min. The starting time was the first time step, i.e. moment 1. The rain cluster lasted for 109 moments, totaling 654min. The target cluster was located in the southwest of Guangdong Province. The convective cloud core occurred at moment 57 and formed in the east of the cluster (Figure 1b). At the moment, the rain cluster was at the front edge of low pressure and moved from southwest to northeast under the influence of steering current (Figure 1c). Rain clusters with the radar reflectivity factor greater than 20dBZ had a maximum area of 9,400 km². Since the convective cloud core existed at moments 57-77, moments 1-56 constituted the development stage of rain clusters, moments 57-77 the mature stage and moments 78-109 the attenuation stage (Figure 1d).

Figure 1 Tracking results of rain clusters. (a) Radar reflectivity factor in South China at moment 57, with the black box showing the target rain cluster and white+ showing the weighted centroid position of the rain cluster; (b) Schematic diagram of the scope of the target rain cluster at moment 57, where the blue area has reflectivity greater than 20dBZ and the red area has reflectivity greater than 40dBZ; (c) The moving path of the weighted centroid of the target rain cluster, in which the filled color shows the time; (d) The radar reflectivity (purple curve, dBZ) and area (yellow curve, 100*km²) of the target rain cluster at 1km changing with time (red dotted line: moment 57; black dotted line: moment 77)
4. Analysis on evolution characteristics of hydrometeors

4.1. Analysis on the evolution of liquid phase particles

The location, duration, motion trail, area and radar reflectivity evolution of the recognized target rain cluster have been introduced above. In this section, the rain cluster will be distinguished between convective cloud cores and stratiform clouds around cores, and the evolution characteristics of their hydrometeors will be analyzed. For rain clusters with the reflectivity factor greater than 20dBZ, the recognition results include cloud cores and surrounding stratiform clouds. Therefore, rain clusters with the reflectivity factor greater than 20dBZ are mixed cloud clusters. Among cloud clusters, those with the reflectivity factor greater than 40dBZ are convective cloud cores and those remained after removal of cloud cores are stratiform clouds around convective cloud cores.

Rainfall rate ($rr$) represents the amount of precipitation per unit time (Figure 2a), which is basically consistent with the evolution characteristics of liquid water content (LWC) (Figure 2b). Convective cores had $rr$ and LWC significantly higher compared to surrounding stratiform clouds. According to Figure 1(b), the convective core had a small area, while surrounding stratiform clouds had a large area. Therefore, the change of the core had limited influence on the mixed rain cluster including the core and its surrounding stratiform clouds. The change of the mixed cloud cluster was similar to that of surrounding stratiform clouds. It is worth noting that the particle diameter ($Dm$) was large at the initial stage of the rain cluster, which gradually decreased with the development of the cluster, while the standardized intercept parameter ($Nw$) representing particle number concentration had a small value at the initial stage and gradually increased with the development of the cluster. This indicates that the rain cluster was mainly composed of large and sparse rain particles at the initial stage of formation and the higher radar reflectivity was mainly contributed by the larger $Dm$. However, $Nw$, $rr$ and LWC had a small value at the time. As the cluster continued to develop, large raindrops broke up, forming smaller raindrops. With the supplement by vapor outside the rain cluster, the raindrop size spectrum gradually changed into the distribution characterized by small and dense raindrops. There were also a large $Dm$ and a small $Nw$ inside the convective cloud core at the mature stage of the rain cluster, i.e. the stage when the core occurred, indicating that the core was also composed of large and sparse raindrops at the initial stage, which was the same as the distribution characteristics of the raindrop size spectrum of surrounding stratiform clouds. For stratiform clouds at the mature stage, $Dm$ reached the minimum while $Nw$ reached the maximum, indicating that stratiform clouds at the mature stage were mainly composed of small droplets with a small particle size but high density. Further particle breakage was the main process at the stage. Stratiform clouds had an increased $Dm$ and decreased $Nw$ at the attenuation stage, indicating the collision-coalescence process of main particles at this stage. $Dm$ also increased and $Nw$ decreased at the end stage of the convective core, indicating that the collision-coalescence process was dominant inside the core (Figures 2c and d).
4.2. Analysis on the evolution of ice phase particles

According to the analysis on the distribution and evolution of liquid phase particles, liquid phase particles in the convective core and stratiform clouds around the core had similar evolution characteristics at the development and attenuation stages. However, ice phase particles had significantly different distribution and evolution characteristics. High-density graupel particles in stratiform clouds mainly appeared at a height of 4-6km with a frequency below 0.1. They began to appear when stratiform clouds developed to a specific stage and disappeared at the end of the mature stage (Figure 3a). Low-density graupel particles mainly existed at a height of 6-20km, with a content higher than that of high-density ones, which mainly provided ice cores for supercooled water condensation. They appeared with a higher frequency at 14-20km and earlier than high-density ones and disappeared later than the latter, indicating that the process of density increase of graupel particles existed at the stage of precipitation enhancement (Figure 3b). Both high-density and low-density graupel particles in the convective core had a much higher frequency than those in stratiform clouds. The former mainly appeared at the height of 4-6km (Figure 3c), and the latter at the height of 5-10km. The duration of low-density graupel particles was shorter than that of high-density ones, indicating that a large number of high-density graupel particles already existed in the convective core. The density of graupel particles did not show significant changes at the time (Figure 3d).
According to the distribution of the frequency of occurrence at different heights, the frequency of high-density graupel particles in stratiform clouds was mainly between 0 and 0.02 and was the highest at the height of 5km. The height with the frequency greater than 0.01 was mainly between 4 and 6km (Figure 4a). The frequency of low-density graupel particles was mainly between 0.1 and 0.5. High values, more than 0.4, were concentrated at the height of 14-20km where there was hardly any liquid water. Low-density graupel particles were mainly formed by ice crystals through hooking, and their frequency decreased greatly at the height of 6-12km (Figure 4b) where supercooled water was possible. As the frequency of wet snow increased within the height range (figure omitted), one of the reasons for the decrease of low-density graupel particles was that wet snow formed due to collision and coalescence with supercooled water, providing conditions for further formation of high-density graupel particles. It's worth noting that it is necessary to continue to study whether the significant reduction of low-density graupel particles in a specific area can serve as indirect proof of the existence of a large amount of supercooled water in the area for further in-depth understanding of the distribution of water resources in the air as it is difficult to judge whether there is supercooled water in the developing convection system directly from observation\cite{18}. The frequency of high-density graupel particles in the convective core increased significantly than that of those in stratiform clouds, mainly ranging from 0.4 to 0.8. The height with the frequency greater than 0.3 was mainly between 4 and 7km (Figure 4c). The frequency of low-density graupel particles was scattered, mainly between 0.2 and 0.8, at the height of 6-8km (Figure 4d).
5. Summary and conclusion

This paper analyzed the variation features of the drop spectrum of liquid-phase hydrometeor particles and the evolution law of ice-phase hydrometeor particle types in convective cloud cores and surrounding stratiform clouds in a strong precipitation process in South China based on Lagrange tracking method, mainly using S-band dual-polarization radar data. The following main conclusions were made:

1) Convective cloud cores and surrounding stratiform clouds can be recognized effectively with different radar reflectivity thresholds based on Lagrange tracking method.

2) Stratiform clouds and convective cloud cores were composed of large and sparse raindrops at the early stage of development. Stratiform clouds were mainly composed of small droplets with a small particle size but high density at the mature stage mainly involving the process of particle breakage. At the attenuation stage, the collision-coalescence process was dominant in stratiform clouds and convective cloud cores.

3) The frequency of high-density graupel particles in stratiform clouds mainly ranged from 0 to 0.02 and was the highest at the height of 5km. The height with the frequency greater than 0.01 was mainly 4-6km. The frequency of low-density graupel particles was mainly between 0.1 and 0.5 and high values were concentrated at the height of 14-20 km. Their content was higher than that of high-density ones. The density of graupel particles increased at the stage of precipitation enhancement. The frequency of high-density graupel particles in the convective core increased significantly than that of those in stratiform clouds, mainly ranging from 0.4 to 0.8. The height with the frequency greater than 0.3 was mainly 4-7km. The frequency of low-density graupel particles was also higher than that of those in stratiform clouds. They mainly appeared at the height of 6-8km. The density of graupel particles did not show a significant change process.

Only one rain cluster in a strong precipitation process was selected and an analysis was conducted on the evolution characteristics of hydrometeors in convective cloud cores and surrounding stratiform clouds in this paper, which can provide scientific basis for our understanding of the causes of variations in water resources in the air in South China and more reasonable use of clean energy such as water resources. However, the results have some limitations due to inadequate cases in the study, so it is necessary to analyze more data to make universal conclusions.

Acknowledgments
This research is supported by National Natural Science Foundation of China (42075077) and Key
technology development project of meteorological forecast of CMA: YBGJXM (2018)1A-10.

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