Numerical study on the evolution of cloud microphysical characteristics during rainfall processes of typhoon Bolaven in 2012

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Abstract. The cloud microphysical characteristics in a rainfall process of typhoon Bolaven is studied by the WRF model. The results indicate that the maximum values of different cloud microphysical parameters occur at different times, strong ascending motions have an important impact on the evolution of cloud microphysics. More than four hours before the peak of rainfall, ascending motions are strongest and occur primarily above the 0°C layer, water vapor is lifted to the upper troposphere and frozen. With increasing rainfall, the core of the strong ascending motion decreases. When the core of the strong ascending motion decreases below the 0°C layer, the amounts of both rainwater and cloud water increase rapidly and reach their maximums at and after the peak, respectively. The vertically integrated cloud water content maintains its maximum for approximately three hours in torrential rain, and cloud water is continuously collected by rainwater.

1. Introduction

The effects of various cloud microphysical characteristics on the intensity, structure and evolution of rainfall have been thoroughly studied[1-2]. However, the microphysical characteristics and mechanisms of clouds vary among different stages of rainfall development. Some numerical investigations have analyzed cloud microphysics at different typical moments or have calculated the mean values of cloud microphysics during important time periods and then inferred the cloud microphysical evolution[3-4]. However, different model grid points may simultaneously experience multiple stages of rainfall. For example, as a rain band moves through a simulation area, rainfall may be increasing at some grid points but decreasing at other grid points. Therefore, the mean results may not truly reflect the cloud microphysical mechanisms that cause such increases and decreases in rainfall. How do cloud microphysical characteristics evolve during rainfall? What are the major cloud microphysical mechanisms that cause rainfall to increase and decrease? In this study, we attempt to answer these questions.

The Weather Research and Forecasting (WRF) model can effectively reproduce the occurrence and evolution of complex rainfall events and simulate cloud microphysics[5]. In the present study, the rainfall processes associated with Typhoon Bolaven in 2012 are selected and simulated using the WRF model. The purpose of this paper is to investigate the evolutionary trend of cloud microphysics and develop a thorough understanding of the cloud microphysical mechanisms in rainfall cycles.
2. Case description

Fig. 1a showed the track and center intensities of Bolaven taken from the China Meteorological Administration-Shanghai Typhoon Institute (CMA-STI) best-track dataset (http://tcdata.typhoon.org.cn/), and Fig. 1b displayed the spatial distribution of the 24-hour accumulated rainfall in the period from 0040 UTC on 28 Aug to 0040 UTC on 29 Aug 2012 provided by an hourly merged precipitation product. This product combined Climate Prediction Center Morphing (CMORPH) technique satellite data with the records of approximately 30,000 automatic weather stations in China at a spatial resolution of 0.1° × 0.1°. Considering that the terrain in Liaoning Province is relatively flat and that Bolaven was a tropical storm when it passed over this area, the present study focuses solely on the rainfall processes in Liaoning Province (40°-43°N, 121°-125°E), marked by the red rectangle in Fig. 1a.

Fig. 1 (a) The track of Typhoon Bolaven based on the CMA-STI best-track data. The colored dots represent the position of the typhoon center every 6 hours. The blue dots denote a violent typhoon, the green dots denote a severe tropical storm, the red dots denote a tropical storm, and the purple dots denote the extratropical transition of the typhoon. The red rectangular box indicates the area of interest in this study. (b) The spatial distribution of the 24-hour accumulated rainfall (units: mm) associated with Bolaven in the period from 0040 UTC on 28 Aug to 0040 UTC on 29 Aug 2012 based on the hourly merged precipitation product.

3. Model simulation and analysis method

3.1. Model setup

Fig. 2 displayed the model grid configuration, which included an outer domain and two nested inner domains centered at 41.70°N, 122.30°E. The outermost domain (d01) was 2943 km × 2457 km with a 27 km grid resolution, the middle domain (d02) was 1980 km × 1629 km with a 9 km grid resolution, and the innermost domain (d03) was 660 km × 543 km with a 3 km grid resolution. All domains had 39 variable vertical layers from the surface to approximately 50 hPa. The meteorological data for the model’s initial and boundary conditions were provided by the European Centre for Medium-Range Weather Forecasts Reanalysis-Interim (ERA-Interim) 0.75° × 0.75° gridded reanalysis dataset at 6-hour intervals. The model runs started at 0000 UTC on 27 Aug 2012, and the model was integrated for 60 hours to capture the passage of Bolaven over Liaoning Province. The time steps were 270 s, 270 s and 90 s for d01, d02 and d03, respectively. In this paper, the analysis time period was specified to range from 0400 UTC on 28 Aug to 0400 UTC on 29 Aug 2012.
This study used the Purdue-Lin scheme for cloud microphysics schemes, the Dudhia scheme for shortwave radiation, the Rapid Radiative Transfer scheme for longwave radiation, the Noah land surface scheme for the land surface, and the Eta Mellor-Yamada-Janjic scheme for the turbulent kinetic energy (TKE) boundary layer in all three domains. The Kain-Fritsch scheme was applied for the cumulus convection in outermost and middle domains, but the cumulus parameterization was turned off in the innermost domain since convection was explicitly resolved.

Fig. 2 The spatial configuration of the domains used for the WRF model simulations. Shading indicates the terrain (units: m).

3.2. Comparison with the observations
The observed and simulated 6-hour accumulated rainfall results were presented in Fig. 3. The simulated intensities in the early stages of rainfall had a low bias. Nevertheless, the model fundamentally captured the rainfall evolution after Bolaven made landfall over Liaoning Province.

Fig. 3 The distributions of the 6-hour accumulated rainfall (units: mm) from 0400 UTC to 1000 UTC on 28 Aug (a, e), 1000 UTC to 1600 UTC on 28 Aug (b, f), 1600 UTC to 2200 UTC on 28 Aug (c, g), and 2200 UTC on 28 Aug to 0400 UTC on 29 Aug (e, h) as provided by the hourly merged precipitation product (a-d) and the simulation with the WRF model (e-h).

3.3. Analysis method
In the present study, a method is proposed to investigate the evolution of cloud microphysical characteristics and mechanisms during rainfall. The curves displayed in Fig. 4 a-c show the rain rate variations at three randomly modeled grid points in the innermost domain. The bottom horizontal axes...
show the UTC time. For each model grid point experiencing precipitation, we set the rainfall peak time \((P_{\text{max}})\) to a standard time (time 0) and set the one-hour, two-hour, and three-hour times before (after) the peak to relative times of -1 (+1), -2 (+2) and -3 (+3), respectively (shown by the upper horizontal axis). All the rain rate curves for the model grid points are centered at the peak time (i.e., time 0), and the synthesized rain rate variation is presented by the red curve in Fig. 4d. The main advantage of this method is that increasing and decreasing rainfall stages can be effectively distinguished. Furthermore, the complex rainfall processes are simplified into a sample rain event that increases first and then decreases.

To further illustrate the differences in the evolution of the cloud microphysical characteristics among various rainfall processes, all model grid points were categorized into four groups, namely, light rain (0-2.5 mm/h), moderate rain (2.5-8.0 mm/h), heavy rain (8.0-16 mm/h) and torrential rain (16.0 mm/h), based on the number of rainfall peaks. Because the grid points characterized by light rain account for less than 2.0% of all grid points, we focus mainly on moderate rain, heavy rain and torrential rain events in the following analyses.

Fig. 4 The curves in (a)-(c) represent the simulated hourly rain time series at three randomly selected WRF model grid points in 3 km domains. The bottom X-axis shows the UTC time, while the upper X-axis is the newly established relative time axis. The red curve in (d) represents the synthesized curve, and the X-axis shows the relative time. The vertical dashed blue lines denote the times when the hourly rain rate reaches its maximum.

4. Cloud microphysical characteristics and mechanisms of rainfall

4.1. Analysis of cloud vertical motion
The shaded areas with warm and cool colors in Fig. 5a-c indicated descending and ascending motions, respectively. With the development of rainfall, the core of the strong ascending motion gradually decreased to below the 0℃ layer. The variation trend of ascending motion was more obvious in torrential rain events. On the other hand, the ascending motions weaken with time, which may result from the effect of the drag force on falling raindrops that restrain convection in low cloud layers.

4.2. Analysis of cloud water
The evolutionary trends of cloud water are displayed in Fig. 5 d-f. Cloud water was distributed mainly below the -20°C layer, and its maximum value was located below the 0°C layer. At times more than two hours before the peak, there were few differences in the vertical distributions of cloud water among moderate rain, heavy rain and torrential rain events. With the development of rainfall, the contents of cloud water significantly increased at levels warmer than 0°C, and the supercooled water
contents changed slightly with time. After the peak, the cores of maximum cloud water contents were increasingly lowered during all rainfall processes. These variations in cloud water were consistent with the variations in strong ascending motions.

The evolutionary trends of the vertically integrated cloud water content were shown in Fig. 5g. In various rainfall events, the vertically integrated cloud water content increased first and then decreased. However, the vertically integrated cloud water content was maintained at its maximum for approximately two or three hours after the peak in heavy rain and torrential rain events. In heavy rain and torrential rain events, the atmosphere below 4.5 km was dominated by ascending motions, and water vapor was lifted by updrafts and continuously condenses to form cloud water. Descending motions became more pronounced at lower levels after the peak in moderate rain events, and thus, water vapor could not be lifted, causing the vertically integrated cloud water content to decrease rapidly.

4.3. Analysis of rain water

Fig. 5 h-j displayed the evolution of the rainwater content. Rainwater was distributed mainly at temperatures above 0°C. At times more than two hours before the peak, in all rain events, the centers of high rainwater contents were located at heights between 2.0 and 4.0 km, and the rainwater content decreased with decreasing height due to the evaporation of raindrops as they fall. With the enhancement of surface rainfall, the rainwater content increased, and its distribution expanded across the surface. In addition, the rainwater content was largest at the peak and decreased monotonously after the peak.

5. Summary

On basis of high-resolution numerical simulation data of the rainfall processes associated with
Typhoon Bolaven simulated by the WRF model, the evolutionary trends of cloud microphysical characteristics and mechanisms during rainfall were analyzed in this study by analyzing the cloud microphysics centered at the rainfall peak time at each 3 km resolution grid point. The main conclusions were summarized as follows:

The evolutionary trends of cloud microphysical characteristics were closely related to the evolution of strong ascending motion. With the development of rainfall, the core of the strong ascending motion generally decreased to low levels in heavy rain and torrential rain events, decreasing to below 8.0 km two hours before the peak. At this time, water vapor was lifted to the 0℃ layer and then condensed, resulting in a rapid increase in the cloud water content. After the peak, the variation in cloud water exhibited a trend similar to that of the variation in the strong ascending motion.

The vertically integrated cloud water and rainwater contents both increased initially and then decreased during different rainfall processes. The maximum values of the vertically integrated rainwater and cloud water contents appeared at and after the peak, respectively. Due to strong ascending motions distributed mainly at levels below 8.0 km in heavy rain and torrential rain events, the vertically integrated cloud water content remained stable with high values from the peak to three hours after the peak. In addition, abundant cloud water was continuously accreted by rainwater, contributing to rainfall.

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