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Cloud-scale simulation study on the evolution of latent heat processes of mesoscale convective system accompanying heavy rainfall: The Hainan case

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ABSTRACT

This paper investigates the structure of latent heat budgets and dynamical structure of mesoscale convective systems (MCS) accompanying heavy rain using a cloud-scale model WRF simulation for the Hainan case. Results show that: (1) according to the fractions skill score and HK scores, the WDM6 scheme is more suitable to predict the rainfall than other microphysical schemes. (2) During the lifetime of MCSs, the top two heating microphysical processes are water vapor condensed into cloud water and water vapor condensed into rainwater. The total latent heat is closely related to the top two heating processes. However, the change of latent heat released by some microphysical processes is not identical with the different rainfall processes. (3) The total latent heat of MCS1 increases during the short life, while the total latent heat of MCS2 and MCS3 reach maximum during the mature stage. The difference is mainly caused by the latent heat of water vapor condensed into cloud water and rainwater. The total latent heat released by cond and rcond of MCS1 is smallest during the mature stage, while it is largest during the mature stage of MCS2 and MCS3. (4) The vertical motions are different with different MCSs. The descending motion of the short-lived process (MCS1) is strongest during the mature stage. It caused the smallest latent heat released by water vapor condensed into cloud water and rainwater at the same period. Besides, there are some differences in the change of latent heat released by microphysical processes of MCS2 and MCS3, which are closely related to the drag force of the vertical motion.

1. Introduction

Heavy rainfall is one of the main types of natural weather conditions in Southern China. Heavy rainfall frequently results from mesoscale convective systems (MCSs) that accompany monsoon fronts and typhoons. An MCS occasionally brings sudden and excessive amounts of precipitation locally, thus causing loss of lives and extensive damage to properties. MCS frequently occurs in South China, East China and Huang-Huai River valley (Wang and Cui, 2011, 2012; Meng et al., 2003, 2005; Zheng et al., 2013; Wang et al., 2014). Fundamental details about MCS can be found in the work of Houze (1993). To better investigate the various characteristics of MCS, high-resolution observational data such as remote-sensing Doppler radar data are used (e.g., Kim and Lee, 2006; Park and Lee, 2009) and high-resolution numerical experiments are conducted (e.g., Lin et al., 2005; Parker, 2007; Lauwaet et al., 2009; Peters and Schumacher, 2015). Several numerical studies have demonstrated that MCS is difficult to simulate in real cases because initial and boundary data are not sufficiently enforced to identify storms. Therefore, many studies have suggested that data assimilation is a useful tool to improve initial simulation conditions (e.g., Chang et al., 2008; Takuya et al., 2014; Hou et al., 2015).

Microphysical processes affect the dynamical structure and thermodynamic process of MCS (e.g., Li et al., 2002; Wang and Yang, 2003; Lou et al., 2003; Fu and Guo, 2006; Gao et al., 2006; Wang et al., 2009; Li et al., 2013a,b). Adams-Selin et al. (2013) measured the sensitivity of five parameters that are important to operational forecasters to graupel properties: timing of bowing development, system speed, wind gusts, system areal coverage and accumulated precipitation. The significant differences in bow-echo characteristics produced by graupel property variations in convective-resolving models emphasize careful microphysical parameterization design. Huang and Cui (2015) studied the dominant cloud microphysical processes of torrential rainfall. They found that the orders of magnitudes of the various hydrometers and sinks in the strong precipitation period were larger than those in the weak precipitation period, causing a difference in the intensity of precipitation. The latent heat released by microphysical processes has an effect on the development and evolvement process of the mesoscale convective system and it changes the conformation of the cloud system, its movement and the intensity and the distribution of the convective

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cloud clusters (Tao et al., 2012). The cooling effect of latent heat (evaporation, melting and sublimation) affect the mesoscale downdraft (Fujita, 1959; Brown, 1979), and the heating effect of latent heat (condensation, freezing and desublimation) strengthen the convective motion (Sun and Tan, 2001; Xu et al., 2011). The cold outflows caused by surface evaporative cooling of rain steered the MCS to move away from its original place (Zhao, 2015). Despite considerable progress, a considerable amount of information remains unknown on the cloud microphysical processes of MCS and the structure of the latent heat budget. These related works lacked quantitative calculations and detailed analyses of cloud microphysical processes and associated heat budgets in MCS.

The primary objective of this study was to investigate the differences among latent heat processes in different MCS stages. The weather research and forecasting (WRF) model is used to conduct simulation experiments for the Hainan case. Every associated latent heat budget is calculated, and the results focus on cloud microphysical process and the structure of latent heat budgets at different MCS stages.

This paper is organized as follows. Section 2 presents the description of the MCS case and relative synoptic environment. Section 3 summarizes the model and design of the experiment. Section 4 is a verification of the simulation results. Section 5 is the evolution of the MCSs. Section 6 investigates characteristics of latent heat budgets in different MCS stages. Section 7 shows the vertical profiles of latent heat. Finally, Section 8 is a summary of our findings.

2. Case description

Rainfall lasting 9 days from the night of September 30, 2010 to October 9, 2010 was the longest process in Hainan Island since 1961. From September 30th to October 2nd, the heavy rainfall began. Large and heavy rains occurred in Wanning, Sanya, Baoting and Lingshui. On October 3rd, the heavy rainfalls occurred in most areas of Hainan Island. On October 4th, the rainfall continued to increase. Because of the tropical disturbance strengthening into tropical depression by October 5th, the rainfall peaked. According to the records of automatic weather stations, the maximum accumulated precipitation amount from 0000 UTC to 2400 UTC on 5 October was 881.80 mm in Qionghai Chaoyang hydrological station. On October 6th, the strong rainfall weakened. On October 7th, heavy rainfall occurred again in Haikou. From the 8th to the 9th, Hainan Island continued to experience rainfall. According to preliminary statistics, the direct economic losses stood at 1.131 billion yuan. This paper chose the rainfall which happened from 0000 UTC to 2400 UTC on 5 October to analyze because of the intensity, which is caused by the convergence of southeast low-level jet and east low-level jet accompanying the tropical depression and the cold air from the north.

3. Numerical model and experiment design

The WRF model (V3.4.1) and its 3D-VAR component, i.e., WRF-VAR, are used in the regional forecasting of heavy rainfall events. On a Mercator conformal map, the model is set up with triple two-way interactive nested domains (Fig. 1) with horizontal grid spacing of 27, 9 and 3 km. The model top is at 50 hPa and 37 sigma layers are used in the vertical. The Grell–Devenyi ensemble scheme (Grell and Devenyi, 2002) is used for the two outermost domains (D01 and D02). For the finest domain (D03), no cumulus parameterization scheme (CPS) is used because such schemes are not designed for horizontal and vertical grid spacings smaller than about 5–10 km (Molinari and Dudek, 1992). The following physics model settings are used on all domains: rapid radiative transfer model longwave scheme (Mlawer et al., 1997), Dudhia shortwave scheme (Dudhia, 1989), Noah land-surface model (Chen and Dudhia, 2001), Monin–Obukhov surface layer scheme (Monin and Obukhov, 1954), and the Mellor–Yamada–Janjic planetary boundary layer scheme (Mellor and Yamada, 1982). In this paper, five different microphysical schemes (WDM5, WDM6, WSM6, Lin and Morrison) are used to test the sensitivity of rainstorm simulation. The initial and boundary

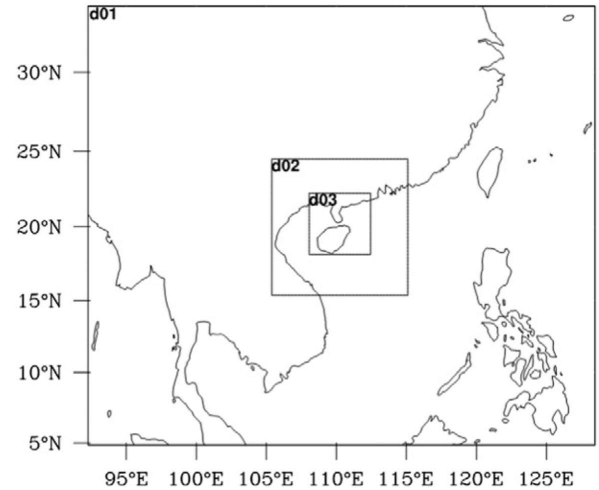

Fig. 1. The experiment domain setting: nested domains for D01, D02 and D03.

conditions are interpolated from the global grid reanalysis data from the National Centers for Environmental Protection/National Center for Atmospheric Research with a 1 × 1 spatial resolution and 6 h temporal resolution. The forecast period is 24 h from 0000 UTC to 2400 UTC on 5 October 2010 with a time step of 150 s. Besides, we utilize the 6-hr "warm start" spin-up from 1800 UTC to 2400 UTC on 4 October. The simulation output has an interval of 30 min. To improve the simulation results, the experiment includes the radar velocity (Vr) and reflectivity (Z) data of the Doppler weather radar in the assimilation at 0000 UTC on 5 October. The design of the control experiment is illustrated in Table 1.

Descriptions of each of the microphysics schemes, its hydrometeor classes and double-moment classes, are provided in Table 2. In this paper, we select the single-moment and double-moment schemes that have six hydrometeor classes. We are also doing some research on the importance of graupel, for simplicity, to make a comparison with the work, we include WDM5 in this paper. The WSM6 (Hong and Lim, 2006; Lin et al., 1983) schemes have some differences in parameters of calculation, while their parameterization processes are similar. The WDM5 and WDM6 schemes (Lim and Hong, 2010) include double-moment rainwater and cloud water distributions, and cloud condensation nuclei (CCN) as a prognostic variable, are different in hydrometeor classes. The WDM5 scheme has no graupel. The Morrison scheme (Morrison et al., 2009) is the most complex scheme used, and has four double-moment classes.

4. Verification of the simulation results

4.1. The neighborhood methods

With the increase of the resolution of model, the traditional verification strategies can't represent the forecast performance well. Recent

Table 1
Designing of the control experiment.

Domain	DOM1	DOM2	DOM3
Horizontal grids	150 × 130	121 × 121	160 × 154
Grid spacing	27 km	9 km	3 km
Integration time	0–24	0–24	0–24
Cumulus parameterization	Grell–Devenyi	Grell–Devenyi	Not used
Microphysics	WSM6	WSM6	WSM6
	WDM5	WDM5	WDM5
	WDM6	WDM6	WDM6
	Lin	Lin	Lin
	Morrison	Morrison	Morrison
Planetary boundary layer	MYJ	MYJ	MYJ