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Effects of latent heat in various cloud microphysics processes on autumn rainstorms with different intensities on Hainan Island, China

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ABSTRACT

In this study, we used the Weather Research and Forecasting (WRF) and WRF-3DVAR models to perform a series of simulations of two autumn rainstorms on Hainan Island. The results of neighborhood fractions and Hanssen skill scoring (FSS, HSS) methods show that the control experiments reproduced well two heavy rainfall episodes. Effects of latent heat in various cloud microphysical processes are different at distinct intensities or stages of precipitation. In the absence of any heating effect of deposition, precipitation weakened. The greater was the precipitation, the more significant was the weakening effect. Ascending movement at upper troposphere could be weakened or descending movement at lower troposphere enhanced. With decreases in the strength of precipitation, cloud ice, snow, graupel, and rainwater, increases in latent heat lessened. With weak precipitation, at upper troposphere the rainwater content increased and snow and ice content decreased, whereas at middle troposphere, the ice, snow, and graupel contents increased. Latent heating increased at middle and lower troposphere and decreased at upper troposphere. The absence of any heating effect of freezing had little effect on precipitation. By removing the evaporative cooling of cloud water, the interactions between vertical movement and cloud microphysical processes resulted in a weakening of strong precipitation and an intensification of weak precipitation. However, in the preliminary stages of these two precipitation events, snow, graupel, cloud ice, and rainwater all increased, and precipitation was enhanced in both. In the later stages, strong precipitation systems weakened and weak precipitation systems strengthened. Latent heating first increased and then dropped in strong precipitation systems, whereas they continuously increased in weak precipitation systems.

1. Introduction

In the Golden Week of China's National Day (October 1st) in 2010 and 2011, continuous rainstorms occurred on the island province of Hainan, causing human casualties and great properties losses and significantly impacting the tourism industry. Hainan's geographical location is unique, being located in the South China Sea (SCS) with high mountainous ground in the island center and lower lands all around. October is the SCS summer monsoon withdrawal period, and the causes of rainstorms are complex. Cloud microphysical processes play an important role in the development and evolution of cloud, precipitation and weather systems. First, the phase transition processes between hydrometeors in clouds that either directly release or absorb latent heat affect the vertical structure of the atmosphere. Secondly, descending hydrometeors will generate a drag effect, which directly impacts the strength and distribution of the ascending airflow. Thirdly, cloud microphysical processes can affect land-surface processes. Fourthly, cloud particles can absorb, scatter, and reflect radiation and influence the energy balance. Due to limitations in detection technology, numerical modeling is frequently used to explore cloud microphysical processes (e.g., Sui et al., 2005; Zhu and Zhang, 2006; Rogers et al., 2007; Li and Pu, 2008; Tao et al., 2011; Li et al., 2013a, 2013b; Li and Shen, 2013; Fernández-González et al., 2016; Jiang et al., 2016; Huang and Wang, 2017). Because of the different precipitation mechanisms associated with different seasons, regions, geographical environments, and

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weather systems, many kinds of microphysics schemes have been proposed. Most researches have focused on individual cases and the conclusions are not necessarily applicable to other cases. Huang and Wang (2017) showed that hydrometeors over the Pacific warm pool have unique microphysical processes relating to their development and depletion. Hence, a better understanding of the cloud microphysical properties of autumn rainstorms in Hainan would be an important contribution.

Through mesoscale and cloud-scale models, most works aim to develop a deeper understanding of cloud microphysical processes (e.g., Jankov et al., 2005, 2007; Zhu and Zhang, 2006; Gao et al., 2006; Rogers et al., 2007; Thompson et al., 2008; Rosenfeld et al., 2012; Lin et al., 2011; Li et al., 2013a, 2013b; Guo et al., 2015; Fernández-González et al., 2016; Sarkadi et al., 2016; Huang and Wang, 2017). Previous researches have had two main focuses: the first has been to gain knowledge about the cloud microphysical processes of typhoons or summer rainstorms (e.g., Zhu and Zhang, 2006; McFarquhar et al., 2006; Pattnaik and Krishnamurti, 2007; Rogers et al., 2007; Li and Pu, 2008; Lin et al., 2011; Tao et al., 2011, Li et al., 2013a, 2013b; Jiang et al., 2016) and most of these studies have involved a comparison of sensitivity test results of various microphysical schemes. In general, the study results have indicated that microphysics schemes do not greatly influence a typhoon's track, but do affect its intensity and structure. Secondly, researchers have sought to improve cloud microphysical schemes to more accurately analyze parameterization calculations for certain hydrometeors (e.g., Thompson et al., 2004; Straka and Mansell, 2005; Thompson et al., 2008; Dudhia et al., 2008; Adams-Selin et al., 2013;Morrison and Milbrandt, 2015; Barthe et al., 2016). For example, Adams-Selin et al. (2013) used the Weather Research and Forecasting (WRF) model to study the effect of graupel size and descending final velocity on precipitation. The authors found that larger size and greater falling velocity leads to more precipitation. Barthe et al. (2016) showed that graupel fall speeds can influence the occurrence of lightning flashes in tropical cyclones.

Cloud microphysical processes include phase transformation and temperature change in hydrometeors, which can cause latent heating or cooling, and thereby affect the vertical structure of the atmosphere and dynamic field (e.g., Zhang, 1989; Tao and Simpson, 1989; Yin et al., 2000, Levin et al., 2005, Flossmann and Wobrock, 2010; Li and Shen, 2013; Adams-Selin et al., 2013; Guo et al., 2015; Fernández-González et al., 2016; Sarkadi et al., 2016; Huang and Wang, 2017). Zhang (1989) used a mesoscale static model to simulate the June 1977 Johnstown floods in the United States and found that growth in condensation and deposition favored the development of a middle-level warm center. In their simulation of a tropical squall line, Tao and Simpson (1989) found different main microphysical processes of precipitation in a convective region and a stratiform cloud area and that the main processes in the precipitation maturation and extinction phases differed as well. Wang (2002) discovered that the evaporation of rainwater and the melting of snow and graupel play a vital role in the generation of tropical cyclonic rain bands and sinking airflow. Colle et al. (2005) found that condensation, melting, deposition of snow, and collection of cloud water by rainwater were important microphysical processes in orographic rain. Wang et al. (2010) and Shen et al. (2011a, 2011b) stated that the influence of cold cloud on precipitation was more significant than the influences of vertical wind shear and radiation in South China precipitation prior to the flood season. The authors found that cloud ice collected by snow and snow collected by graupel were the critical microphysical processes during the development of cold cloud. Using a 2-D cloud model, Li and Shen (2013) investigated the rain microphysical processes in tropical deep convection. Huang and Wang (2017) showed that liquid-phase hydrometeors dominate the evolution of thunderstorms over the Pacific warm pool.

The focus of the above studies was the overall effect of a certain microphysical process and most related to typhoon or rainstorm in summer. However, each cloud microphysical process is associated with many influence factors and there are also a variety of parameter calculation methods. In this study, we focus on the impacts of latent heating (or cooling) in various cloud microphysical processes on autumn rainstorms with different intensities on Hainan.

This paper is organized as follows. An overview of the case studies is described in Section 2. In Section 3, we describe our experimental design. In Section 4, we verify the results of our control experiment. We perform a comparative analysis of the results of three sensitivity experiments in Section 5 and we summarize in Section 6.

2. Overview of individual cases of rainstorm

2.1. Case A

The nine-day rainstorm from September 30 to October 09, 2010 in Hainan was the longest duration of heavy rain since 1961. The average precipitation over the whole island reached 648.3 mm—six times higher than the average of the same period from 1951 to 2009 (93.1 mm). From the time meteorological recordkeeping began in Hainan in 1951, the maximum daily precipitation ever recorded (881.8 mm) at a single station occurred in Boao town, Qionghai City on October 5. With its nine day duration, this rainstorm also broke the record for the maximum duration of a continuous rainstorm. The direct economic losses totaled 13.4 billion dollars.

Judging from the 500 hPa circulation field (Fig. 1), Hainan was in the south of the area with a subtropical high from September 29 to October 2, and east wind prevailed. There was a tropical disturbance in the region of 5°N–15°N, 95°E–100°E. The upper-air chart of October 5 showed

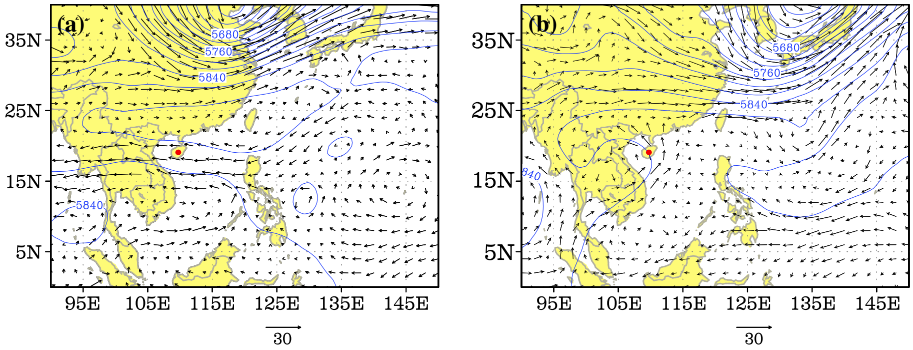

Fig. 1. Wind (black arrow, unit: m/s) and geopotential height (blue line, unit: gpm) at 500 hPa at (a) 1200 UTC 2 Oct; (b) 0000 UTC 5 Oct 2010. Red filled circle indicates location of Hainan Island.