Simulation of the evolution of the latent heat processes in a mesoscale convective system accompanied by heavy rainfall over the Guangzhou region of South China

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ABSTRACT
A cloud-scale WRF simulation was used to investigate the cloud microphysical processes and three-dimensional structure of latent heat budgets in different stages of a mesoscale convective system (MCS) accompanied by heavy rain that occurred in the Guangzhou region of South China. The results enable us to draw the following conclusions: (1) During the development and mature stages, the main heating processes were condensation below 400 hPa and deposition above 400 hPa. The main cooling processes were evaporation and melting. During the dissipation stage, all the microphysical processes were weak. (2) Water vapor condensed into cloud water, and rainwater significantly contributed to all stages of the MCS. (3) During every stage of the MCS, the primary cooling microphysical process was the evaporation of rainwater, which was maximum during the mature stage.

1. Introduction
Heavy rainfall, one of the major natural weather conditions in South China, frequently results from mesoscale convective systems (MCSs) that accompany monsoon fronts and typhoons. An MCS occasionally brings sudden and excessive amounts of local precipitation that can cause loss of lives and extensive damage to properties. MCSs frequently occur in North and South America, India, China, Africa, and Australia, and many studies related to this phenomenon have been published (Maddox 1980; Maddox, Rodgers, and Howard 1982; Rodgers, Magnano, and Arns 1985; Augustine and Howard 1991; Laing and Fritsch 2000; Meng et al. 2005; Chang, Chen, and Cheung 2008). To investigate the various characteristics of MCSs, researchers have used high-resolution observational data from remote-sensing Doppler radar (e.g. Bluestein and Jain 1985; Hagen, Schiesser, and Dorninger 2000; Kim and Lee 2006; Park and Lee 2009) and conducted high-resolution numerical simulation experiments (e.g. Lin, Wang, and Schlesinger 2005; Meng et al. 2005; Parker 2007; Chang, Chen, and Cheung 2008; Lauwaet, van Lipzig, and De Ridder 2009). The results from several numerical studies have demonstrated that actual MCS cases are difficult to simulate because the initial and boundary data are not sufficiently enforced to identify storms. Therefore, many studies have suggested data assimilation as a useful tool for improving initial simulation conditions (e.g. Chang, Chen, and Cheung 2008).

On the basis of observational studies, Maddox (1980) demonstrated the significance of warm air advection and moisture supply on the development of MCSs. Mid-level warm core structures and upper tropospheric mass outflows, which are induced by the latent heat release associated with deep convective clouds, are typically observed in mature MCSs. Clouds in different geographical locations may have different microphysical structures (Lin, Wang, and Schlesinger 2005). The study of cloud microphysical processes is important for understanding mesoscale
precipitation systems (e.g. Li, Sui, and Lau 2002; Lou et al. 2003; Wang and Yang 2003; Fu and Guo 2006; Gao, Ping, and Li 2006; Wang et al. 2009; Li et al. 2013a, 2013b). Cloud microphysical processes and the concomitant changes in the heat budget affect the structure and development of an MCS. However, previous MCS studies have focused on the mechanisms of development (e.g. Maddox 1980; Zhang and Fritsch 1988; Fritsch, Murphy, and Kain 1994; Chen, Wang, and Hsieh 2003; Parker 2007; Choi et al. 2011). Despite considerable progress, there is a substantial amount of information on the cloud microphysical processes of MCSs and the 3D structure of their latent heat budgets that is still unknown. Previous studies on MCSs lack quantitative calculations and sufficiently detailed analyses of cloud microphysical processes and their associated heat budgets.

Our primary objective in this study was to investigate the differences between the latent heat processes of different MCS stages. We used the WRF model to conduct simulation experiments at a 3-km cloud-resolving resolution for a case that occurred in the Guangzhou region of South China. We calculated the transformation rate and associated latent heat budget to characterize the cloud microphysical processes and 3D structure of the latent heat budget of each of the different MCS stages.

This paper is organized as follows: In Section 2, we describe the MCS case we studied and its relative synoptic environment. In Section 3, we describe the model and design of the experiment. In Section 4, we verify our simulation results. In Section 5, we discuss the latent heating rate during the evolution of the MCS. In Section 6, we characterize the latent heat budgets of the different MCS stages. Finally, in Section 7, we summarize our findings.

2. Case description

On 6 May 2010, from 1200 to 2400 UTC, a heavy rainfall event occurred over the Guangzhou region of South China. Guangzhou was located at the center of the heavy rainfall event, and 221 measurement sites recorded more than 50 mm of rainfall. The 12-h accumulated precipitation was greater than 200 mm over the Guangzhou area. The maximum accumulated precipitation recorded over the 12 h was 213 mm in Wushan, and in 1 h the accumulated precipitation in Wushan was 99 mm at 1800 UTC 6 May 2010. We chose this case because the operational numerical weather prediction was made without data assimilation and failed to forecast this event. Heavy rainfall events such as these cause serious water-related disasters in Guangzhou.

3. Numerical model and experiment design

The WRF model and its three-dimensional variational (3D-VAR) component, known as WRF-VAR, are used generally in the regional forecasting of heavy rainfall events. On a Mercator conformal map, the model was set up with triple two-way interactive nested domains with horizontal grid spacings of 27, 9, and 3 km. The model maximum was at 50 hPa and 37 sigma layers were used in the vertical direction. We used the Betts-Miller-Janjic cumulus parameterization scheme (CPS) (Janjic 1994) for the two outermost domains (D01 and D02). For the finest domain (D03), we used no CPS. We used the following physics model settings on all domains: the WRF double-moment six-class microphysics (WDM6) parameterization scheme (Lim and Hong 2010), the RRTM longwave scheme (Mlawer et al. 1997), the Dudhia shortwave scheme (Dudhia 1989), the Noah land-surface model (Chen and Dudhia 2001), the Monin–Obukhov surface layer scheme, and the Mellor–Yamada–Janjic PBL scheme (Mellor and Yamada 1982). We interpolated the initial and boundary conditions from the global gridded reanalysis data of NCEP–NCAR, with a 1° × 1° spatial resolution and 6-h temporal resolution. We initialized the model at 1200 UTC 6 May 2010 and integrated it for 12 h until 2400 UTC 6 May 2010. The simulation output was in intervals of 60 min. To improve the simulation results, we included in the assimilation experiment the radial velocity and reflectivity data of the Doppler weather radar.

4. Verification of the simulation results

Figure 1 presents the observed TRMM precipitation data, with a 0.25° × 0.25° spatial resolution, and the simulated distribution of the accumulated rainfall, from 1200 UTC to 2400 UTC 6 May 2010 in Guangdong Province in D03. From the TRMM precipitation data, we can see that the main rainfall occurred in the east-central area of Guangdong Province, with more than 200 mm of heavy rainfall in the center. The simulated rain belt was located west of the observation data. One of the rainfall centers was well simulated, although the intensity was slightly overestimated.

Since the 12-h accumulated precipitation did not reflect the discontinuity and suddenness of the rainstorm, we analyzed the hourly precipitation (Figure 2). The rainfall at Wushan station mainly occurred from 1700 to 2100 UTC, with the heaviest rainfall occurring between 1700 and 1800 UTC. The simulated rainfall (23.0831°N, 113.336°E) mainly occurred from 1400 to 1900 UTC. While the observed rainfall was heaviest between 1700 and 1800 UTC, it was approximately 20 mm heavier than the simulated rainfall. Between 1400 and 1700 UTC, the observed rainfall was weaker than the simulated rainfall; whereas between 1900 and 2100 UTC, the simulated rainfall was weaker than the observed rainfall. In conclusion, the simulation experiment reproduced the main characteristics of this intense rainstorm.
5. Structure of the latent heating rate during the MCS’ evolution

The latent heat released by hydrometeor transformation supplies energy for MCS development, and the drag effect of hydrometeors affects MCS structure. In this experiment, we used the WDM6 cloud microphysics scheme, which includes six hydrometeors (water vapor, cloud water, rainwater, cloud ice, snow, and graupel) and 38 cloud-microphysical transformation processes.

To calculate and analyze the cloud microphysical processes and latent heat, we classified them into six categories, as follows: condensation (con), evaporation (evp), deposition (dep), sublimation (sub), freezing (frz), and melting (mlt). We neglected processes without phase changes. We calculated the latent heating rates as follows:

\[
q_{\text{con}} = L_v \times \left( P_{\text{con}} + P_{\text{rcond}} + P_{\text{ac}} \right) / C_{\text{pm}},
\]

\[
q_{\text{evp}} = L_v \times \left( P_{\text{evap}} + P_{\text{revp}} + P_{\text{grevp}} + P_{\text{sevp}} \right) / C_{\text{pm}},
\]

\[
q_{\text{frz}} = L_f \times \left( P_{\text{frz}} + P_{\text{gfrz}} + P_{\text{iafrz}} + P_{\text{giafrz}} + P_{\text{ssfrz}} + 2 \times P_{\text{aacw}} \right) / C_{\text{pm}},
\]

\[
q_{\text{mlt}} = L_f \times \left( P_{\text{melt}} + P_{\text{gmlt}} + P_{\text{imelt}} + P_{\text{semelt}} + P_{\text{gemelt}} \right) / C_{\text{pm}},
\]

\[
q_{\text{dep}} = L_s \times \left( P_{\text{dep}} + P_{\text{sdep}} + P_{\text{gdep}} + P_{\text{igen}} \right) / C_{\text{pm}},
\]

\[
q_{\text{sub}} = L_s \times \left( P_{\text{sub}} + P_{\text{ssub}} + P_{\text{gsub}} \right) / C_{\text{pm}},
\]

\[
q_{\text{total}} = q_{\text{con}} + q_{\text{evp}} + q_{\text{frz}} + q_{\text{mlt}} + q_{\text{dep}} + q_{\text{sub}},
\]

where \( q_{\text{con}}, q_{\text{evp}}, q_{\text{frz}}, q_{\text{dep}}, q_{\text{mlt}} \) and \( q_{\text{sub}} \) are the latent heating rates of condensation, evaporation, freezing, melting, deposition and sublimation, respectively; \( C_{\text{pm}} \) is the heat capacity of moist air at constant pressure; \( L_v, L_f \) and \( L_s \) are the latent heat of condensation, fusion, and sublimation, respectively; and \( p_{\text{xxx}} \) is the conversion rate of a specific microphysical process (see Table 1 for their definitions).

Using the hourly rainfall (Figure 2), we chose three periods in which to analyze the characteristics of the latent heat budgets in different stages of the MCS. Figure 3 presents the average regional (23°N–23.35°N, 112.8°E–113.2°E) structure of the latent heating rate for different MCS stages.

During the development stage (Figure 3(a), 1300–1400 UTC), condensation mainly occurred between 900 and 300 hPa, indicating the condensation of large quantities of supercooled water. The condensation rate reached 13 °C h\(^{-1}\). Evaporation dominated below 200 hPa. Freezing was observed mainly around 500 hPa, and reached a rate of 1.5 °C h\(^{-1}\). Cooling by melting occurred between 500 and 700 hPa, and a maximum rate of more than −3 °C h\(^{-1}\) occurred at 600 hPa. Deposition was the main heating process between 500 and 150 hPa, and the rate reached...
7 °C h⁻¹ at 300 hPa. Sublimation occurred above 550 hPa, with a maximum rate of −2 °C h⁻¹.

During the mature stage (Figure 3(b), 1700–1800 UTC), condensation extended from 1000 to 350 hPa, and the rate was nearly 12 °C h⁻¹. Evaporation by freezing occurred between 600 and 700 hPa, with a maximum rate of more than −6 °C h⁻¹. Freezing occurred between 600 and 400 hPa, with a maximum rate of 1.5 °C h⁻¹ at around 500 hPa. Cooling by melting occurred between 550 and 700 hPa, and reaches a maximum rate of more than −3 °C h⁻¹ at 600 hPa. Deposition heating dominated above 600 hPa, and reached 6 °C h⁻¹. Sublimation occurred above 550 hPa, with a maximum rate of −1 °C h⁻¹.

During the dissipation stage (Figure 3(c), 1800–1900 UTC), the microphysical processes were weak. The condensation rate reached just 1 °C h⁻¹, and the evaporation process reached a maximum rate of only −1.5 °C h⁻¹. As such, the released latent heat of the rainstorm center was insignificant.

6. Characteristics of latent heat budgets

In the WDM6 scheme, 26 microphysical processes involve latent heat, including 14 that release and 12 that absorb latent heat (Table 1). During the development stage, as much as 712.52 × 10¹⁴ J h⁻¹ of latent heat was released. The total positive latent heat released was 1033.01 × 10¹⁴ J h⁻¹, and the top three heating microphysical processes (in bold type) were water vapor condensed into cloud water (cond), water vapor condensed into rainwater (rcond) and graupel deposition growth (gdep). These processes accounted for 93.52% of the total released latent heat. The condensation of water vapor into cloud water was significant, contributing as much as 68.13% to the total volume. Water vapor condensation released 933.02 × 10¹⁴ J h⁻¹ of latent heat, which was greater than that released from other processes. The latent heat released by gdep reached a value of 32.03 × 10¹⁴ J h⁻¹. The negative latent heat was 320.49 × 10¹⁴ J h⁻¹, and the top three cooling microphysical processes (in bold type) were evaporation of rainwater (revp), melting of graupel (gmlt), and evaporation of cloud water (cevp). Their total contribution to the cooling was 85.15%. Rainwater evaporation in the MCS accounted for 16.37%. Cloud water evaporation accounted for a loss of 22.75 × 10¹⁴ J h⁻¹ or 7.10% of the total cooling. The contribution of gmlt to the total cooling was 68.49%. Water vapor condensation released 933.02 × 10¹⁴ J h⁻¹ of latent heat, which was greater than that released from other processes. The latent heat released by gdep reached a value of 32.03 × 10¹⁴ J h⁻¹. The negative latent heat was 320.49 × 10¹⁴ J h⁻¹, and the top three cooling microphysical processes (in bold type) were evaporation of rainwater (revp), melting of graupel (gmlt), and evaporation of cloud water (cevp). Their total contribution to the cooling was 85.15%. Rainwater evaporation in the MCS accounted for 197.68 × 10¹⁴ J h⁻¹ or 61.68% of the total cooling. The contribution of gmlt to the total cooling was 68.13%. Cloud water evaporation accounted for a loss of 712.52 × 10¹⁴ J h⁻¹ or 7.10% of the total cooling. The contribution of gmlt to the total cooling was 68.49%. Water vapor condensation released 933.02 × 10¹⁴ J h⁻¹ of latent heat, which was greater than that released from other processes.
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The evaporation of rainwater accounted for a loss of $363.06 \times 10^{14}$ J h$^{-1}$ or 74.46% of the total cooling in the MCS. The contribution of gmlt to the total cooling was 12.17%. The sublimation of snow accounted for a loss of $16.24 \times 10^{14}$ J h$^{-1}$ or 3.33% of the total cooling.

During the dissipation stage, the release of latent heat decreased to $-93.5 \times 10^{14}$ J h$^{-1}$. The total positive latent heat released was $27.67 \times 10^{14}$ J h$^{-1}$, and the top three heating microphysical processes (in bold type) were the condensation of water vapor to cloud water (cond), deposition growth of cloud ice (sdep), and condensation of water vapor to rainwater (rcond). The condensation of water vapor to cloud water accounted for an increase of $18.95 \times 10^{14}$ J h$^{-1}$ or 68.49% of the total heating. The deposition of cloud ice released accounted for 9.61% of the total heating. The latent heat released by rcond reached $1.81 \times 10^{14}$ J h$^{-1}$ or 6.54% of the total heating. The negative latent heat amounted to $121.17 \times 10^{14}$ J h$^{-1}$, and the top three cooling microphysical processes (in bold type) were the evaporation of rainwater (revp), sublimation of snow (ssub), and evaporation of cloud water into water vapor (cevp). The evaporation of rainwater accounted for a loss of $73.25 \times 10^{14}$ J h$^{-1}$ or 60.45% of the total cooling of the MCS. The contribution of ssub to the total cooling was 21.63%. The evaporation of cloud water accounted for a loss of $9.33 \times 10^{14}$ J h$^{-1}$ or 7.70% of the total cooling.

### 7. Conclusions

The latest generation mesoscale WRF model was used to conduct simulation experiments at a 3-km cloud-resolving resolution for an MCS case associated with heavy rain that occurred in the Guangzhou region of South China. After verifying the simulation results, we examined the cloud microphysical processes and 3D structure of the latent heat budgets in the development, mature, and dissipation stages of the MCS.

With respect to the structure of the latent heating rate, the condensation heating rate was largest during the development stage, and the evaporation heating rate was largest during the mature stage. During the development and mature stages, the main heating process was condensation below 400 hPa and deposition above 400 hPa. The main cooling processes were evaporation and melting. During the dissipation stage, all the microphysical processes were weak.

The total latent heat was greatest during the development stage and provided energy for convection; while during the dissipation stage, the total latent heat was negative and restrained convection. During the development stage, the top three heating microphysical processes were the condensation of water vapor to cloud water (cond), condensation of water vapor to cloud water (cond), vapor to cloud water (cond), condensation of water vapor to rainwater (rond), and deposition growth of snow (sdep). The condensation of water vapor to cloud water accounted for $524.88 \times 10^{14}$ J h$^{-1}$ or 61.66% of the total heating. The latent heat released by rcond totaled $160.24 \times 10^{14}$ J h$^{-1}$. The contribution of sdep totaled 6.58%. The negative latent heat amounted to $487.6 \times 10^{14}$ J h$^{-1}$, and the top three cooling microphysical processes (in bold type) were the evaporation of rainwater (revp), melting of graupel (gmlt), and sublimation of snow (ssub). The evaporation of rainwater accounted for a loss of $363.06 \times 10^{14}$ J h$^{-1}$ or 74.46% of the total cooling in the MCS. The contribution of gmlt to the total cooling was 12.17%. The sublimation of snow accounted for a loss of $16.24 \times 10^{14}$ J h$^{-1}$ or 3.33% of the total cooling.

![Figure 3. Average latent heating rate (units: K h$^{-1}$) at different stages: (a) development; (b) mature; (c) dissipation.](image-url)
condensation of water vapor to rainwater (rcond), and deposition growth of graupel (gdeph). During the mature stage, the top three heating microphysical processes were the condensation of water vapor to cloud water (cond), condensation of water vapor to rainwater (rcond), and deposition growth of snow (sdep). During the dissipation stage, the top three heating microphysical processes were the condensation of water vapor to cloud water (cond), deposition growth of cloud ice (idep), and condensation of water vapor to rainwater (rcond). The contribution of water vapor condensed into cloud water was greatest during the development stage, and caused the greatest total latent heat.

During the development stage, the top three cooling microphysical processes were the evaporation of rainwater (revp), melting of graupel (gmlt), and evaporation of cloud water (cevp). During the mature stage, the top three cooling microphysical processes were the evaporation of rainwater (revp), melting of graupel (gmlt), and sublimation of snow (ssub). During the dissipation stage, the top three cooling microphysical processes were the evaporation of rainwater (revp), sublimation of snow (ssub), and evaporation of cloud water into water vapor (cevp). The contribution of rainwater evaporation was greatest during the mature stage.

The magnitude and range of heat budgets derived from this case simulation are close to previous similar works (e.g. Li et al. 2013a, 2013b). However, the observation of microphysical processes remains very difficult, and therefore more work is needed.

**Disclosure statement**

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