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EFFECTS OF CONDENSATION HEATING AND SURFACE FLUXES ON THE DEVELOPMENT OF A SOUTH CHINA MESOSCALE CONVECTIVE SYSTEM (MCS)

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ABSTRACT: A sensitive numerical simulation study is carried out to investigate the effects of condensation heating and surface fluxes on the development of a South China MCS that occurred during 23 – 24 May 1998. The results reveal the following: (1) Condensation heating plays an important role in the development of MCS. In every different stage, without condensation heating, MCS precipitation is significantly reduced, and quickly dissipates. (2) Condensation heating demonstrates most importantly during the early development stages of MCS vortex; as the vortex develops stronger, the condensation heating effects reduces. (3) By affecting the MCS development processes, condensation heating also influences the formation of MCS mesoscale environment structure features such as low-level jet (mLLJ), upper-level divergence. (4) By changing the antecedent environmental circulation, the surface fluxes also play an important role in the development of MCS. Because of the surface heating, pressure declines over the heavy rainfall and MCS happening regions, which results in the intensification of southerly flows from the ocean along the South China coastline areas, and leads to the enhancement of horizontal convergence and increase of vapor amount in the lower layer. All of these make the atmosphere more unstable and more favorable for the convection.

Key words: condensation heating; surface fluxes; mesoscale convective system (MCS); South China heavy rainfall; numerical simulation

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1 INTRODUCTION

The mesoscale convective system (MCS) is one of the most important systems on the scale that causes destructive heavy rain weather. As shown by observational facts, most of the precipitation in heavy rain processes in southern China, especially those associated with the Meiyu front, come from MCS composed of meso-β and meso-γ scale convective cloud clusters near the frontal surfaces[1, 2]. MCS has been studied at home by means of satellite imagery analysis and numerical simulation methods to gain preliminary knowledge of its development, structure and evolution[3, 4].

The MM5 mesoscale numerical model was used to conduct a successful simulation of a mesoscale MCS during a heavy rain in southern China that took place in May 23 – 24, 1998.

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Some interesting results have been achieved[5]. The simulated MCS, of the meso-β scale, was generated in a vortex on a shear line and persisted for more than 10 hours. Convection inside was intense and its maximum ascending velocity was above 90 cm/s, producing precipitation more than 20 mm/h. There was a mesoscale low-level jet (mLLJ) at the low levels to the right of the MCS and strong southwesterly at the upper levels. Throughout the entire vertical direction, the MCS was displayed inside as a cyclonic column of vortex with the divergence center near 400 hPa.

Other studies find that the formation and development of MCS are closely linked with condensation heating and variation of diabatic processes such as surface water cycles and thermal fluxes, in addition to favorable environmental condition. Quite a number of works have been done on the impacts of condensation heating and diabatic processes in the boundary layer on weather systems, including MCS[6 – 9]. A high system generating over mesoscale convective complex (MCC) was shown due to heating from convective condensation in the simulation of [9], which deals with the structural features of MCC by adding or withdrawing cumulus heating. In contrast to the ambient pressure, the relatively high pressure of the system can enhance upper-level divergence and result in non-compensating shift of mass in the upper air, thus decreasing low-level pressure to induce convergence there and the development of cyclonic vortex. It is then concluded that circulation associated with MCC, including low-level cyclones and upper-level anti-cyclones, are all a direct response to deep convection. Some other work include studies on mid-layer vortexes, warm cores and rear inflows and their relationship with condensation latent heating[10 – 12]. Conclusions thus obtained are also indicative. In southern China, how do these physical processes affect the generation and development of MCS? On the basis of former control experiments, the current work will discuss in detail the generation and development of MCS in southern China by looking at numerical simulations that add or withdraw diabatic processes like condensation heating, surface water cycles and thermal fluxes.

2 EFFECTS OF CONDENSATION HEATING ON GENERATION AND DEVELOPMENT OF MCS AND ITS STRUCTURES

2.1 *Scheme design for the sensitivity experiment*

The scheme design for the mesoscale model used by the current numerical experiment and original control experiment are shown in [5]. For the initial and lateral boundary condition, the reanalyzed data from NCAR/NCEP are used as background field, which are available by performing objective analysis of the observations, provided by the South China Sea Monsoon Experiment (SCSMEX), on model gridpoints. To discuss the role of condensation heating resulted from model precipitation, the term of condensation heating resulted from precipitation, whether it is identifiable or not in the ambient field, is removed from the model equations. In other words, condensation processes can take place on both scales during the model integration, but their warming to the ambient settings are ignored. Regarding previous practice of removing condensation heating right in the beginning of the integration in a number of models, it is the authors' opinion that it cannot give entirely accurate description of the effect of condensation heating on the formation and development of mesoscale systems, especially for cases in which mesoscale systems do not develop until some time after the initial moment of integration. In view of it, three schemes of sensitivity experiments were designed based on the patterns of MCS activity in question and the original control experiment (CNTLE). The schemes are to investigate the role of condensation heating in the initial, maturing and decaying stages of MCS development. For each of the schemes, the model reruns the integration at 00:00 UTC (same below) May 23, 1998 (t = 0 h). For Exp.1(NOCHE-1), when the integration runs to 21:00 May 23 (t = 21 h), about the time when the MCS begins to develop, the condensation heating is removed. For Exp.2

(NOCHE-2) and Exp.3 (NOCHE-3), however, the role of condensation heating is not removed until the integration runs to 02:00 (*t* = 26 h) and 08:00 (*t* = 32 h), respectively. The latter two experiments were used to examine the relative effect of condensation heating in the maturing and decaying stages.

2.2 *Effect of condensation heating on different stages of MCS development and structure*

2.2.1 INITIAL STAGE

As shown in the results, condensation heating plays an important part in the formation and development of heavy-rain-inflicting MCS and its vortex, especially during the initial stage of the vortex. Fig.1 gives the results of integration at *t* = 22 h for CNTLE and *t* = 24 h for NOCHE-1, respectively. Beginning from *t* = 22 h and with the occurrence of the MCS, CNTLE is able to simulate a low-level mesoscale vortex that forms on the 850-hPa shear (Fig.1a & 1c), which displays itself in large-scale cyclonic circulation in South China. In contrast, NOCHE-1, which does not have the effect of condensation heating, fails to simulate the mesoscale vortex. Fig.1b & 1d show the results of 1 h and 3 h into the integration without the effect of condensation heating in corresponding time levels of NOCHE-1. It can be seen that the mesoscale vortex that would be associated with the MCS does not form due to the lack of condensation heating, suggesting an essential role of the latter. It is worth noting that the exclusion affects precipitation by the MCS in addition to restricting the development of the vortex. It is known from Fig.1b & 1d that 1 h after the exclusion of the condensation heating effect, areas with precipitation larger than 20 mm/h are shrinking and rain intensity is decreasing, although areas with precipitation larger than 10 mm/h are increasing. The effect is much more obvious when the model is 2 h or 3 h into the forward integration without consideration of the condensation heating. It is known from Fig.1d that areas with precipitation larger than 10 mm/h already disappear and rain intensity reduces sharply so that MCS cannot develop.

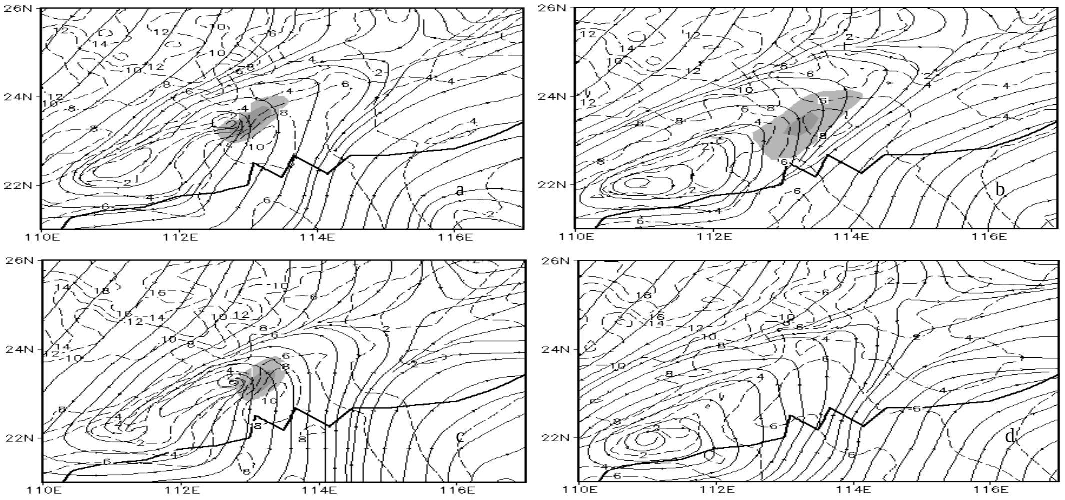

Fig.1 Comparisons of integration results by *t* = 22 h (a) and *t* = 24 h (c) in NOCHE-1 and those by *t* = 22 h (b) and *t* = 24 h (d) in CNTLE. Solid lines with arrows stand for 850-hPa streamlines, dashed lines for isotachs (unit: m/s) and shaded areas are where simulated precipitation is larger than 10 mm and 20 mm, respectively.

2.2.2 MATURING AND DECAYING STAGES

When condensation heating is removed after the MCS develops to the maturing stage, the impact on MCS precipitation is similar to the initial stage in which precipitation decreases rapidly to prevent the MCS from further developing. What is mostly the same is that condensation heating affects a vortex that has already developed to or near full intensity. As shown in the result of the NOCHE-2 experiment, the fully evolved mesoscale vortex has merged with a large-scale vortex with larger horizontal scale; circulation continues to develop though its intensity weakens to some extent when condensation heating is not included. Fig.2 gives the comparisons of the NOCHE-2 at t = 29 h, or 3 h after the removal of condensation heating, and the original control experiment CNTLE.

During the decaying stage of the MCS, however, MCS-induced precipitation has dropped significantly so that the results of the above two experiments do not stand far apart from each other and the effect of condensation heating becomes even less (figure omitted).

2.2.3 IMPACTS ON MCS STRUCTURE

Owing to the effect of condensation heating on the formation and development of vortexes, the development of mLLJ to the right of the MCS during the maturing stage is also much restrained. As shown in the CNTLE experiment, a zone of relatively strong wind already appears on 850 hPa to the right of MCS at t = 22 h (Fig.1a) and wind speed has increased to 14 m/s and more in the zone at t = 29 h, forming a mesoscale low-level jet (Fig.2a) and making a good source of energy for persistent development of the system. Viewing from corresponding levels of time, the NOCHE experiment fails to simulate the mLLJ if condensation heating is not considered (Fig.1b & 1d and Fig.2b). Besides, a strong divergence field originally over the MCS is also much affected and the structure of corresponding divergent flow field is weakened significantly if no condensation heating is included in the maturing stage (figure omitted).

Fig.3 gives the distribution of differences of pressure or geopotential height field and wind field between the surface and 400 hPa at t = 22 h with both CNTLE and NOCHE-1. It is now clearer that condensation heating has given rise to an area of substantial pressure drop at low levels near the MCS due to the effect of condensation heating, as surface pressure has dropped by 2 hPa in front of MCS (Fig.3a) and the descent of low-level isobaric surface height has also extended to layers above 850 hPa (figure omitted). Correspondingly, isobaric surfaces also ascend in the middle and upper levels over the MCS (Fig.3b). Under the circumstance, the effect of pressure gradient force is such that a well-defined convergence of wind fields is formed at lower levels while divergence is the main play at upper levels, which is favorable for the persistent development of convective systems. It is known from the figure that the convergence area of low-level wind fields is mainly in front of the MCS, which displays itself as a shear.

Similar results can be found by comparing the CNTLE and NOCHE-2 experiments. It is also interesting to note that low-level convergence resulted from condensation heating is also in front of the MCS during its maturing stage and shows itself as a line of convergence, which is similar to the initial stage. It agrees with corresponding radar echo (figure omitted) that shows intense convection zone is in front of MCS. It is then known that lines of convergence forming in front of MCS due to low-level condensation heating do not exist by chance.

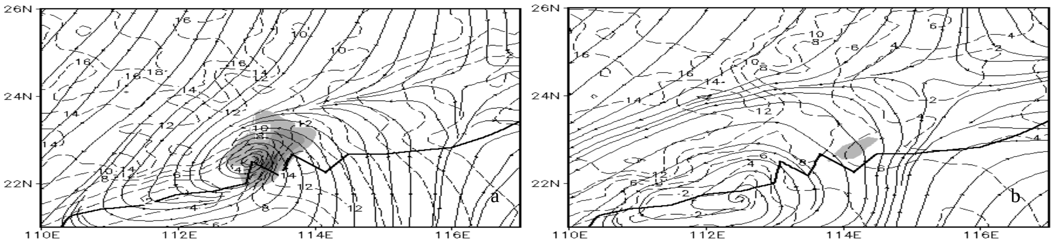

Fig.2 Comparisons of results of the NOCHE-2 (a) and CNTLE (b) experiments at t = 29 h. Other captions are as Fig.1.

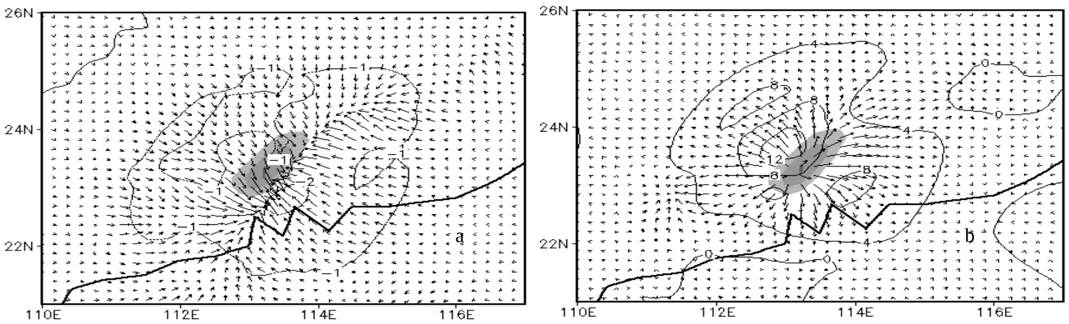

Fig.3 Differences of pressure (with intervals of 1 hPa), the geopotential height field (with intervals of 4 gpm) and wind field in cases with and without condensation heating for the surface (a) and 400 hPa (b) at t = 22 h. (NOCHE-1 is subtracted from CNTLE). Captions for shaded areas are the same as in Fig.1.

Low-level zones or lines of convergence in front of storms are not uncommon in a number of observational studies. It is generally held that they reflect the role of gust fronts generated in front of the storm by descending air motion.[13]. In some of the intensely-developing storms, a PBL mesoscale surface high could form in the rear of the storm because condensed water vapor in sloping ascending flow inside transforms to water droplets that fall and join the descending flows in the rear of the storm before evaporating and cooling down. As the forward outflows of relatively cold air in the high lift the relatively warm and humid air in the front to higher levels, the ascending airflow is revived to provide necessary mechanisms for the persistent development of the system. In view of the fact that the MCS of interest forms within the vortex with a low-level mesoscale low without the presence of any well-defined mesoscale high nor clear descending airflow in the rear part of the system, the lines of convergence or intense convection zones in the front edge of the low-level MCS are thought to be a form of MCS that moves forward and develops persistently.

It is inferred from the above analysis that mesoscale structural features of the system can be affected due to the effect of condensation heating on the generation and development of MCS, on the one hand, and changes in these features also lead to changes in the condition with which the MCS develops persistently, on the other hand.

3 EFFECTS OF SURFACE FLUX ON MCS GENERATION AND DEVELOPMENT

Apart from the effect of condensation heating, diabatic processes such as land surface fluxes also pose important effects on the formation and development of heavy-rain-inflicting MCS and other mesoscale systems. The change in land surface flux not only affects the process of equilibrium for energy and water vapor over land surface but also causes changes in factors responsible for deep convection, and eventually plays a part in the development of convective systems. Through experiments that compare results with and without the settings of land surface sensible and latent heat fluxes, the present section seeks more understanding about the effect of diabatic processes on the generation and development of MCS.

3.1 *Experiment design*

In the original control experiment of CNTLE, the MRF scheme was used in the physical process of the PBL and Dudhia’s 5-layer soil model was used to calculate surface temperature. Successful simulations suggest good descriptive capabilities of these schemes of physics for this MCS that brought heavy rain. To understand more about the role of land surface flux in its formation and development, the following two experiments were designed. Based on the original control experiment, the NOFLE-1 starts its integration without the effect of land surface flux while the NOFLE-2 does not remove it until the model integration runs to $t = 21$ h, i.e. when the MCS begins to grow.

3.2 *Comparing the results of the original control experiment*

As shown in the result of comparison experiment, surface flux contributes a lot to the formation and development of heavy-rain-inflicting MCS. The surface flux affects less when convection is in full swing, as the effect is realized by altering the ambient field preceding to the start of MCS to modify conditions in such a way as to favor the development of convection. Fig.4a & 4b give 24-h accumulative rainfall from 12:00 May 23 to 12:00 May 24 ($t = 12 – 36$ h) for the NOFLE-1 and NOFLE-2 experiments respectively. As shown in the result of NOFLE-1, simulated maximum 24-h rainfall center is about 80 mm if no surface flux is included in model integration, which differs much from the result of CNTLE (Fig.4c). If the surface flux is not removed until after $t = 21$ h in model integration, the result is very similar to that with the original CNTLE experiment. It shows that land surface fluxes have different relative importance depending on the stage of MCS development. Similar findings are also noted in previous work. For example, physical processes in PBL are indispensable in starting up the convective systems in heavy rain but contribute little to its development, a finding documented by Sun et al.[8] in their work on heavy-rain-inflicting MCS and associated ambient fields.

It can be conferred that MCS cannot be simulated in NOFLE-1 for it does not consider the effect of surface flux from the beginning, which changes the evolution of the ambient field and destroys the setting-up of conditions favorable for MCS. When model integration proceeds to $t = 21$ h, however, the conditions for convection to set off are already established and removal of surface fluxes does not make a difference to the continuation of MCS. For a clearer picture of the issue, more detailed study will be conducted next on how surface fluxes actually exert their influence.

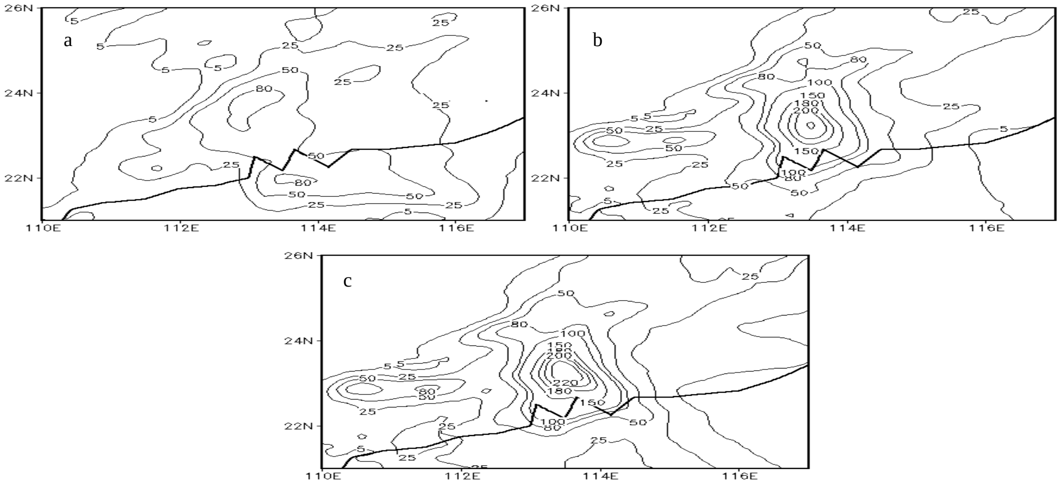

Fig.4 Accumulated 24-h (12:00 May 23 – 12:00 May 24) rainfall with different experiments. a. NOFLE-1; b. NOFLE-2; c. CNTLE. Unit: mm; isolines are respectively 5, 25, 50, 80, 100, 150, 180, 200, 220.

3.3 *Analysis of the effect of sensible and latent heat from land surface*

It is known from Fig.5 that the simulation of diurnal variation of fluxes of surface sensible and latent heat by the 5-layer soil model is quite reasonable. The figure gives the temporal evolution of the fluxes simulated with CNTLE for 3×3 mesh averaged around the MCS. During the nighttime, surface sensible heat cools things down and has a long, obvious period of growth after t = 24 h (08:00 L.T.) and is the maximum (34 W/m^2) when t = 30 h (14:00 L.T.) before weakening gradually (Fig.5a). A maximum value of surface latent heat appears before t = 12 h, which decreases during the night until early morning. Like sensible heat, it also begins to increase significantly after t = 24 h and is as large as 57 W/m^2 at maximum (Fig.5b).

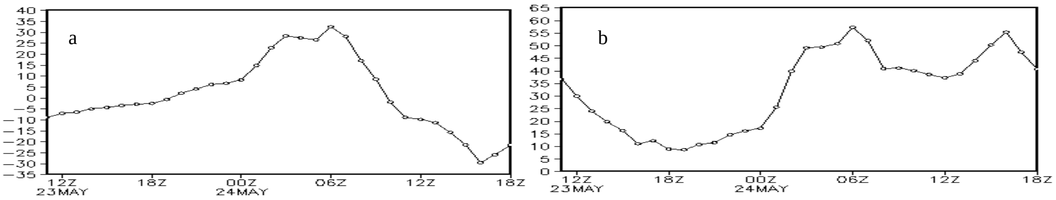

Fig.5 The evolution of the fluxes simulated by CNTLE for a 3×3 mesh averaged around the MCS. a. sensible heat; b. latent heat; unit: W/m^2.

That the MCS appears to grow with the increase of surface flux does not imply that such diabatic process has been key to the development of MCS. It has been shown in the simulations of precipitation by NOFLE-2 that the MCS keeps on thriving once the convection develops, even though no effect of surface flux is included.

Mainly through affecting preceding fields of pressure, airflow, temperature and humidity, land surface fluxes play an important role in the onset of convection and formation of MCS. It is clearly shown in studies on the horizontal distribution of surface flux and meteorological fields. At t = 22 h, as shown in the control experiment CNTLE, the flux of latent heat is positive and heating of such nature is especially strong over the sea surface, even though negative sensible heat flux has already dominated over the region of Pearl River Mouth and areas south of it and is acting to cool (figure omitted). The consequence is that the southwestward inverted trough extending from northern South China Sea to southern China has been strengthened (Fig.6a). Fig.6b is the difference of surface pressure by NOFLE-1 from CNTLE. It shows that the diabatic heating from the surface helps form a zone of pressure drop (with the intensity being –3 hPa) around the Pearl River Mouth and coastal areas west of it, contributing to the deepening of the inverted trough. Further study shows that the pressure drop is associated with the rise of near-

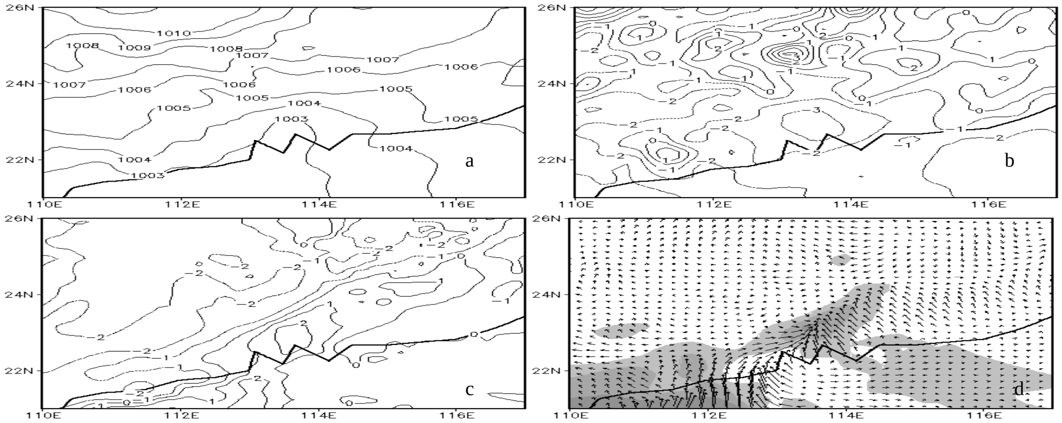

Fig.6 The pressure field simulated by CNTLE at t =22 h (a) and pressure difference at intervals of 1 hPa by subtracting NOFLE-1 from CNTLE at t = 22 h (b), temperature difference at intervals of 1°C (c), and differences in specific humidity (larger than 3 kg/g, 4 kg/g, 5 kg/g) and differences in the flow field (d).

surface air temperature resulted from surface diabatic heating. Fig.6c gives the temperature difference at the height of 2 m by subtracting NOFLE-1 from CNTLE, which clearly shows that a temperature rise zone resulted from surface diabatic heating is corresponding with the zone of pressure drop. It is reasonable for the increase of temperature in the near-surface layer expands the air but reduces the density, causing the pressure to fall. The pressure drop on the coastal areas of southern China increases the pressure gradient pointing from the sea towards the southern part of China to strengthen the southerly wind coming from the northern part of the South China Sea and converge airflow in its coastal area. From the distribution of differences in 10-m-high wind field and 2-m-high specific humidity field by subtracting NOFLE-1 from CNTLE (Fig.6d), it is known that the airflow convergence forming on the southern China coast as a result of increased southerly also increases the moisture content in the air. For the increase of specific humidity, it is above 2 g/kg from the northern part of the South China Sea to southern China, with the maximum between 6 and 7 g/kg. The shaded parts are the areas with specific humidity increased to 3, 4, or 5 g/kg.

Such changes in the near-surface temperature and humidity affect the development of vertical stability and vertical motion in the lower levels of the atmosphere. Fig.7 gives cross sections of vertical space running nearly north-south along the heavy rain and in the MCS development zone at *t* = 22 h for the two experiments of CNTLE and NOFLE-1. In the original control experiment of CNTLE (Fig.7a), low-level air is both warm and humid in the warm sector of the southern cold air mass to give rise to unstable convection within the levels ($\partial q_e/\partial p > 0$) and warm and humid air from the south converges with the cold air in front of the low-level front, contributing to the onset and development of convection and generating significant ascending motion. It is right here that the MCS grows. With the effect of sensible and latent heat fluxes from land surface ignored, the condition favorable for the development of convection is restricted to large extent due to the lack of surface heating and moistening. As shown in Fig.7b, the once unstable stratification has broken down, the southerly wind in the southern edge of the cold air mass weakened and the cold air in the northern edge moved at a faster pace to arrive more southward. It is consistent with the previous analysis. The situation occurs when factors leading to the strengthening of the southerly wind disappear and forces resisting cold air from advancing southward decrease, resulting in reduced convergence of cold and warm air and large restrain of ascending motion ahead of the front.

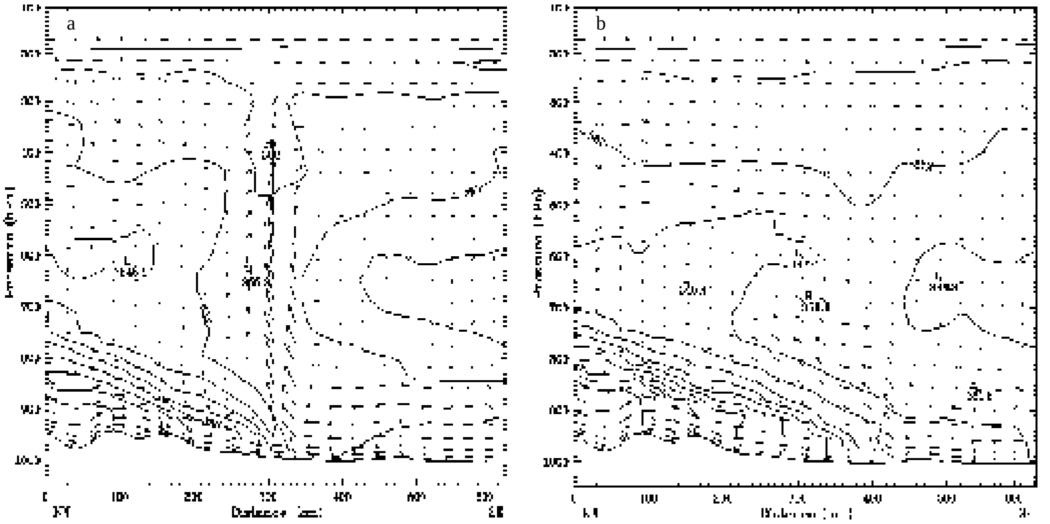

Fig.7 The cross sections of vertical space running nearly north-south along the heavy-rain-inducing MCS zone at *t* = 22 h for the two experiments of CNTLE (a) and NOFLE-1 (b). The solid line is potential temperature with the interval of 4°C and vectors with arrows are the vertical circulation.

4 RESULTS AND DISCUSSIONS

Conducting numerical simulation to compare and study the effect of including or excluding condensation heating and surface fluxes, the present work analyzes the effect of these diabatic processes on heavy-rain-inflicting MCS that took place May 23 – 24, 1998. The phenomena and results obtained are of some indication and help to the study of generation, development and structural features of the MCS in southern China.

a. Condensation heating has large impact on the precipitation caused by MCS, which will weaken the rain intensity in the MCS to prevent it from developing if no condensation heating is included.

b. During the life cycles of the MCS development, condensation heating differs from MCS vortexes in contribution — the former is the most important factor during the formation of MCS vortexes but the impact lessens after the formation.

c. Via the effect on the development of the MCS, condensation heating also affects the formation of mesoscale low-level jets (mLLJ) in the ambient field of MCS and high-level divergence. Without the effect of condensation heating, it is impossible to simulate the mLLJ and the divergence on top of it is also much affected.

d. Diabatic processes such as sensible and latent heat flux from the surface affect the onset of convection and formation of MCS by altering the fields of pressure, airflow, temperature and humidity in preceding periods. During the early stage of heavy-rain-inflicting MCS, these processes decrease the pressure to increase the ocean-originating southerly wind in southern China and strengthen the convergence. As a result, low-level humidity increases and air layer becomes more unstable, favoring the onset of convection. When convection sets off to grow, the effect of surface flux is less significant.

Of course, actual observations and case study results are needed to verify the above phenomena and results in the numerical simulation and comparing experiments, which are noted to be with limitation. In the context of present absence of high-resolution observations, comparing study by way of numerical simulation does shed some light on this aspect, helping us from an alternative angle to understand the workings of the MCS. For example, the latent heat near the Pearl River Mouth and northern South China Sea plays a major role in this heavy-rain-inflicting MCS, as shown in the experiment. The heating increases the ocean-originating southerly wind and favors the transportation of water vapor and the formation of unstable stratification on the coast of southern China. It is then necessary to have more study on ocean and land processes to see if it is true for heavy rain throughout the whole region of southern China.

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