Article ID: 1006-8775(2012) 02-0220-08

DIAGNOSTIC ANALYSIS ON THE DISTRIBUTION OF RAINFALL ASSOCIATED WITH TYPHOON “MOLAVE” (0906)

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Abstract: This work examines the mechanism of rainfall associated with typhoon Molave (0906) in Guangdong province and Guangxi Zhuang Autonamous Region with rainfall observations, radar mosaics from China National Meteorological Center and the final analysis data of National Center of Environmental Prediction (FNL/NCEP, USA). The result shows that the mechanism is different for the rainfall in the these areas. The rainfall in eastern Guangdong is mainly associated with a convective line to the front-right of the typhoon. The convective line is about 200 km away from the typhoon center. The rainfall in western Guangdong and Guangxi appear ahead of or to the left of the typhoon and is very close to the typhoon center. Both rainfall moves forward with the typhoon anticlockwise. It was also found that the rainfall occurred in the boundary between unstable and low-level convergent areas and closer to the convergent area. The unstable area is located in the downstream of rainfall and ahead of the convective line. It is an important factor to the development and convection. Strong frontogenesis is observed in the backward or upstream convective area of rainfall and is thus an important lifting condition for the formation of rainfall. When the low-level convergent area moves to the unstable area ahead of it, the unstable energy is left behind and as a result the convection is strengthened.

Key words: typhoon Molave; rainfall distribution; diagnostic analysis

CLC number: P444 **Document code:** A **doi:** 10.3969/j.issn.1006-8775.2012.02.011

1 INTRODUCTION

China is one of the countries that have the most severe impact from tropical cyclones (TCs). On average, there are 7-8 TCs equal to or stronger than the intensity of tropical storm that make landfall in China. The landfalling TCs may cause heavy rainfall and could be very disastrous to the people’s life and properties[1]. Though the forecast accuracy of the TC track is improved, no big improvement has been seen in TC rainfall forecast. The forecast error of rainfall is substantially large when there is a big uncertainty in TC track forecast[2]. TC associated rainfall has been an important topic in both research and operational communities. Large amount of efforts have been made by domestic and foreign researchers and operational forecasters[3]. Many studies show that the rainfall associated with TC is very complicated with huge difference between different cases[4-6]. TC rainfall is affected not only by TC structure and structure change but also by multi-scale system interactions. This work tries to explore the dynamic and thermodynamic factors that are associated with the rainfall of typhoon Molave in July 2009.

2 AN OVERVIEW OF TYPHOON MOLAVE AND ITS ASSOCIATED RAINFALL

2.1 *Features of the TC*

Tropical storm Molave formed to the east of Luzon Island at night (local time) on 16 July 2009. It moved first to the northwest for one day and then recurved to the northwest (Figure 1). It made landfall on Shenzhen, Guangdong province around 16:50 Coordinated Universal Time (UTC) 19 July. Molave intensified into a severe tropical storm in the morning of 17 July. It became a typhoon in the early morning of 18 July. It reached its maximum intensity at the night of 18 July before making landfall (The maximum wind speed near the TC center is 38 m s^{-1}, and the minimum sea level pressure near the TC center is 965 hPa). Molave got weakened gradually after making landfall. It became a tropical depression in Guangxi Zhuang Autonomous Region. The track of Molave shown in Figure 1 between 1200 UTC 16 July–1200 UTC 20 July was based on the TC center positions given by the *Yearbook of Tropical Cyclones*

Received 2011-09-30; **Revised** 2012-02-17; **Accepted** 2012-04-15

Foundation item: Natural Science Foundation of China (40730948; 40905028; 40975035)

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(2009) edited by Shanghai Typhoon Institute. TC positions at 1800 and 0000 UTC 20 July were obtained by analyzing the circulation center of a 850 hPa flow using the final analysis data of National Center of Environmental Prediction (FNL/NCEP, USA).

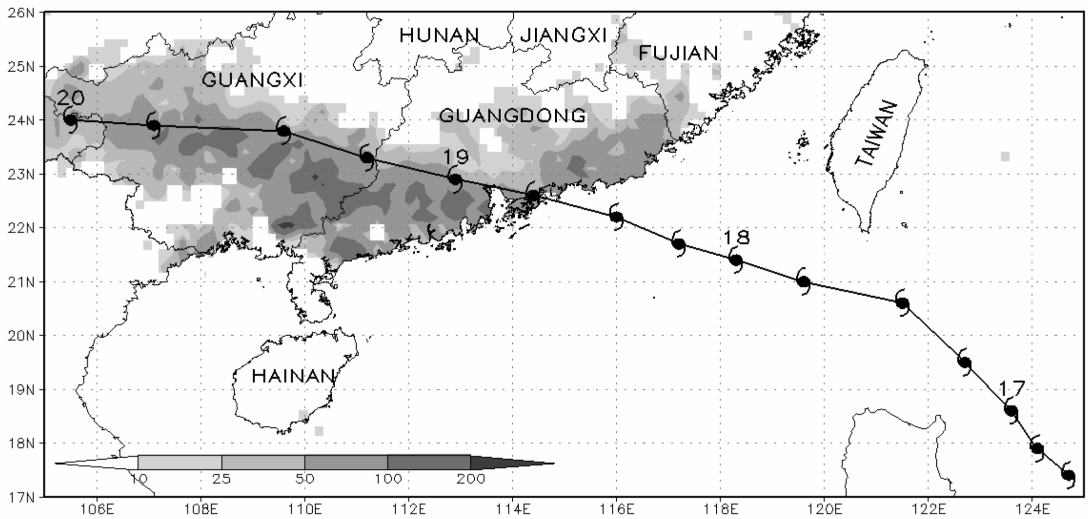

Figure 1. The track of typhoon Molave (2009) and the location of its remnant circulation center (every six hours) from 1200 UTC 16 July and 0000 UTC 20 July 2009, and the 48-h accumulated rainfall (shaded, unit: mm) from 0000 UTC 18 to 0000 UTC 20 July. The number shows the date and the adjacent typhoon symbol is the location of the typhoon at 0000 UTC.

2.2 *Features of the rainfall*

Affected by the outer cloud system of Molave, heavy rainfall appeared in the coastal area of eastern Guangdong, southern Guangxi, etc. The main rainfall period was during 0000 UTC 18 July–0000 UTC 20 July. In the above mentioned area, 50-100 mm rainfall was observed with larger-than-100 mm rainfall in part of the area (Figure 1). A process rainfall of larger-than-250 mm was observed at Beiliu (332 mm), and Bobai (297 mm) in Guangxi and Dianbai (288 mm) in Guangdong. The heavy rainfall caused severe disasters to the buildings and crops in the two regions.

If we define the rainfall intensity as the amount of hourly rainfall, the area with large accumulated rainfall all have large rainfall intensity during their main rainfall periods. The maximum rainfall intensity was generally larger than 20 mm h^{-1} and sometimes even larger than 50 mm h^{-1}. In Luoding, Yunfu of Guangdong, and Yulin and Beiliu of Guangxi, the maximum rainfall intensity was 112, 90 and 95 mm h^{-1}, respectively (Figure omitted).

2.3 *Daily rainfall and verification of rainfall forecast*

Previous observational and numerical studies show that heavy rainfall generally appears in the front-right quadrant with respect to the moving direction of the TC during or after landfall in Northern Hemisphere. This asymmetric structure may be due to the frictional convergence to the right of the TC track. Figure 2 shows the operational forecast of rainfall (thin solid line in Figure 2) at 0000 and 1200 UTC July 18 before the TC made landfall and at 0000 UTC 19 July after the TC made landfall as well as the corresponding observational rainfall (shaded). The forecasted rainfall at 0000 UTC 18 July before the TC made landfall (Figure 2a) is mainly in the front-right quadrant of the TC while the forecast rainfall is mainly near the TC center around and after the landfall (Figure 2c), which is significantly different from the observed rainfall distribution—with the heavy rainfall mainly appearing on the left of the TC track.

2.4 *Synoptic overview*

During 0000 UTC 18 July–0000 UTC 20 July 2009, the Yangtze River valley was dominated by the strong subtropical high on 500 hPa. Strong easterly winds to the south of the ridge of subtropical high control the area to the south of the Yangtze River and south of China. The TC and its remnant circulation are located to the south of the subtropical high. Steered by wide easterly winds, the TC moves west northwest at speeds of 20-30 km h^{-1}. This situation basically determined that the rainfall associated with this TC will appear in Guangdong and Guangxi. Besides, as Molave is affecting them, the moisture condition is very beneficial. Most of Guangdong and Guangxi have precipitable water of larger than 50 kg m^{-2}. This moisture condition is a very important contributor to the formation of heavy rainfall.

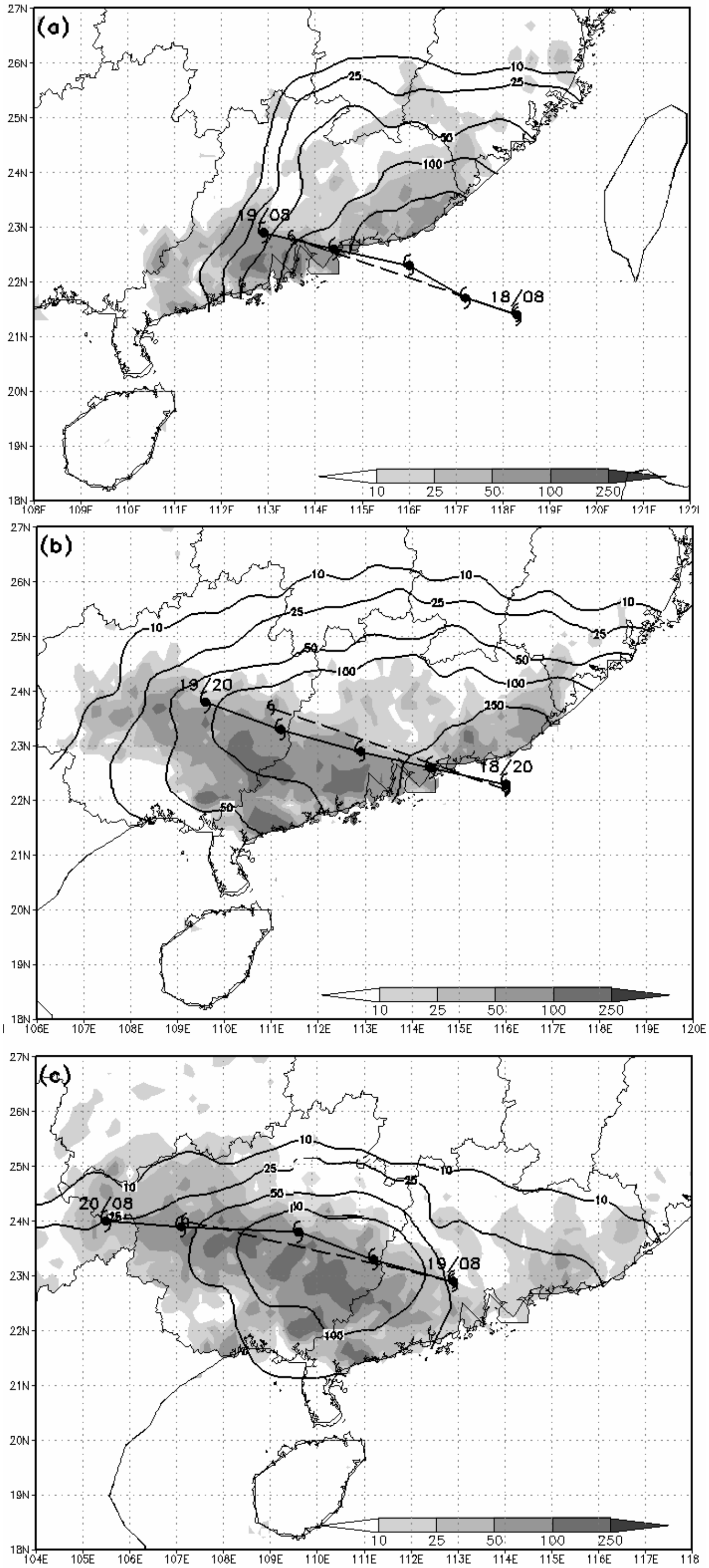

Figure 2. The 24-h forecast rainfall (thin solid line, unit: mm) and the 24-h actual accumulated rainfall (shaded, unit: mm), and the location of typhoon (every six hours). a: 0000 UTC 18 July 2009; b: 1200 UTC 18 July 2009; c: 0000 UTC 19 July 2009.

3 RAINFALL FEATURES ON RADAR MOSAICS

The radar mosaic of the maximum radar reflectivity in the vertical column (Figure 3) and the infrared satellite imagery (Figure omitted) show that a weak convective line appeared outside of the TC offshore of Shantou in southeast Guangdong when the TC was located in the northeast part of South China Sea, about 200 km away from the coastal line of east Guangdong (Figure 3a) and more than 10 hours before the TC made landfall on Shenzhen, Guangdong in the early morning of 19 July. While the TC was moving steadily to the west-northwest, the convective line also entered Guangdong and moved to the west (Figure 3b) and turned anti-cyclonically around the TC center (Figure 3c). The convective line intensified gradually with an apparent increase of the extent of a 45-50 dBZ area. The strong convective area shifted gradually from the front-right quadrant at the initial stage to the front and left of the TC track while intensifying. In the early morning of 19 July, the convective line weakened gradually and moved to the sea (Figure 3d). The strong rain belt near the core of the TC remained about 200 km away from the convective line. The intensity of the rainband near the core of the TC did not change much during the intensifying process of the convective line.

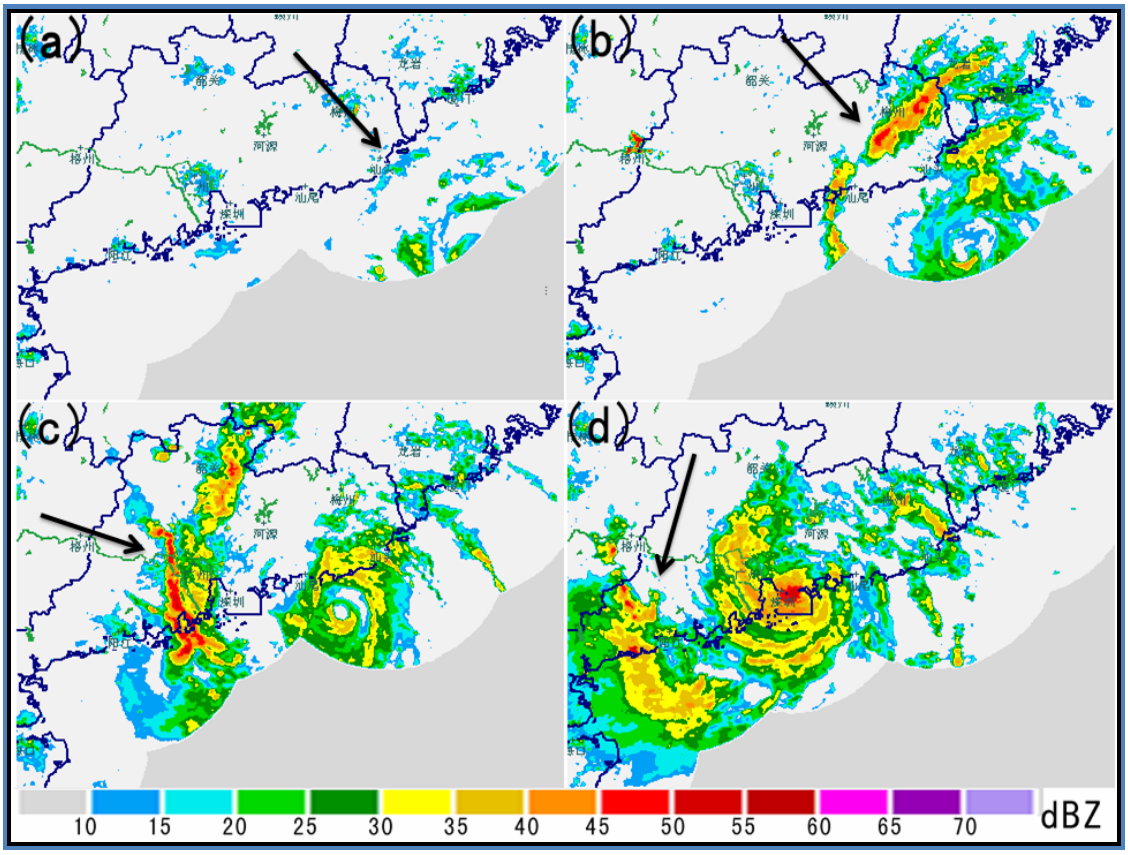

Figure 3. The radar mosaic of composition reflectivity (unit: dBZ) in the south of China, the endpoint of a black arrow shows the location of the convective line at the typhoon’s periphery. a: 0000 UTC; b: 0600 UTC; c: 1200 UTC; d: 1800 UTC 18 July 2009.

When the convective line weakened and moved anticlockwise to the sea, the weakened TC depression kept moving to the west, around which a large area of convective cloud developed. As a result, extensive heavy rainfall appeared in the middle and eastern parts of Guangdong and middle and southern parts of Guangxi (Figure omitted).

The rainfall process associated with Molave can be classified into two stages: (1) Guangdong rainfall, which consists of rainfall associated with the convective line and TC core. The former may be formed under the interaction between the TC and its environment. (2) Guangxi rainfall, which is likely due to the interaction between the weakened TC core and its environment. As will be shown in the following sections, the two stage rainfall are all related to the thermodynamic instability in the front of the convection and the dynamic disturbance associated with the approaching of the TC.

4 DYNAMIC AND THERMODYNAMIC DIAGNOSIS

There is a large area of unstable air with large convective available potential energy (CAPE) in southeastern Guangdong (Figure 4a). With the approaching of the TC, weak echo (as pointed by the black arrow in Figure 3a) appears in the region where the unstable area overlaps with the outer area of disturbance of the TC (the convergence). The unstable and convergent area is apparently to the front-right direction of the TC track with the unstable area in front or downstream of the convergent area. Over time, the unstable and convergent area gradually shift from the right-front to the front (Figures 4b and 4c), and later on the left-front direction, of the TC track (Figure 4d). In other words, the convective line turns anticlockwise around the TC center while moving forward as a whole with the TC. This feature can be clearly seen from the radar reflectivity imagery (Figures 3a-d). The convective line stays between the unstable and convergent area and is slightly closer to the convergent area.

To further analyze the dynamic features of the rainfall process, we examined the frontogenesis at different levels with the following equation[7]:

$$F=\frac{\mathrm{d}}{\mathrm{d}t}\left|\nabla_h\theta\right|=\frac{-1}{\left|\nabla_h\theta\right|}\left\{\left[\left(\frac{\partial\theta}{\partial x}\right)^2\left(\frac{\partial u}{\partial x}\right)+\left(\frac{\partial\theta}{\partial y}\right)^2\left(\frac{\partial u}{\partial y}\right)\right]\right. \quad (1)$$

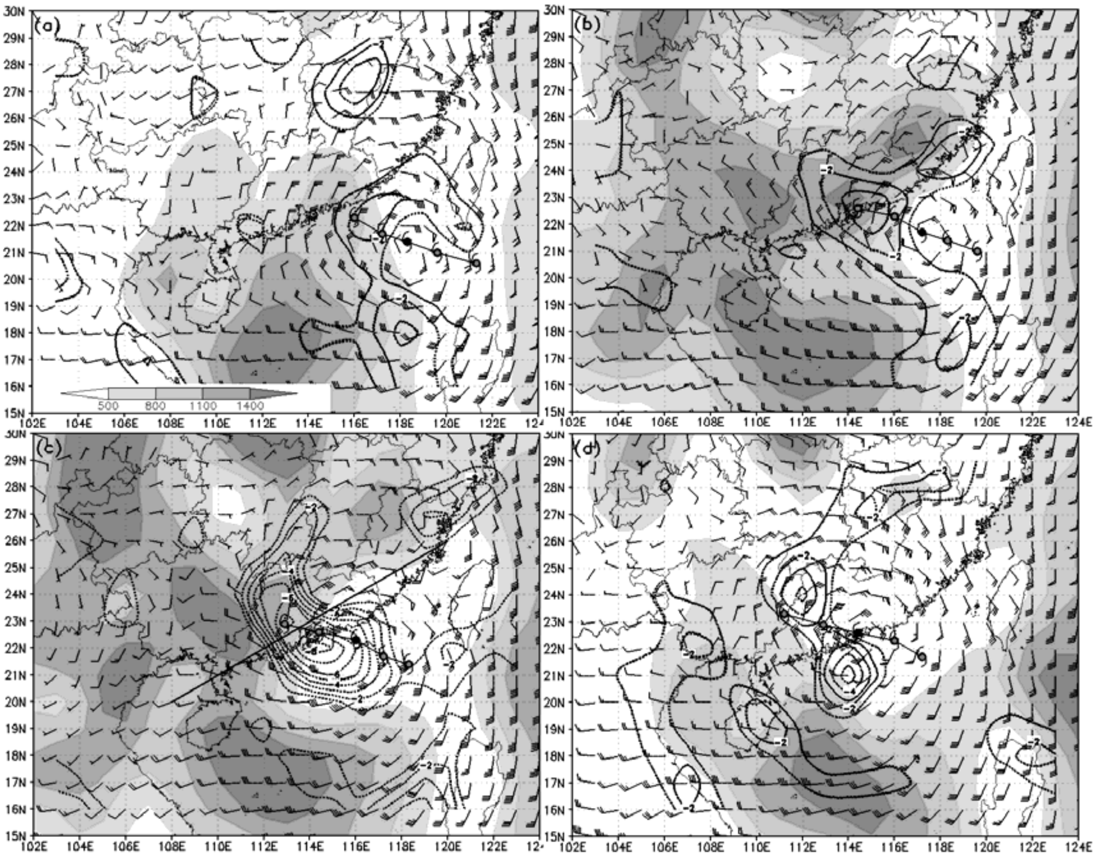

Figure 4. The distribution of the surface convective available potential energy (CAPE) (shaded, unit: J kg^{-1}) and the divergence at 850 hPa (dash line, the negative values show the convergence, unit: 10^{-5} s^{-1}). a: 0000 UTC; b: 0600 UTC; c: 1200 UTC; d: 1800 UTC 18 July 2009.

Comparing Figure 5a and Figure 4c, we found that the frontogenesis area almost overlaps with the area with upward motion and horizontal convergence. We call this area a dynamic lifting region. The convective line is located between the unstable area and the area of dynamic lifting while being slightly closer to the dynamic lifting center. At 1200 UTC 18 July, Yangjiang of Guangdong (denoted by the red "+" in Figure 5a) is positioned in front of the convection with a CAPE of 3310 J kg^{-1} as calculated using the radiosonde observation (Figure 5b), which shows a very strong unstable environment.

This phenomenon also applies to the rainfall in Guangxi on July 19 (Figure 6) though the rainfall area in Guangxi is closer to the TC center than that in Guangdong. This indicates that with the weakening of the TC, the extent of the TC shrinks and thus the dynamic condition that can trigger the releasing of CAPE only get close to the TC center. The hourly rainfall from 0500-0600 UTC on 19 July is shown in Figure 6a, which is almost overlapping with the convective line on radar reflectivity imagery at 0600 UTC (Figure omitted). Figures 6a-6b demonstrate that the most intense rainfall (the darker shaded area in Figure 6a) is located to the front-left of TC track and on the boundary between the 850 hPa convergence and unstable area and gets slightly closer to the convergent area. The rain belt extends in a similar direction as the long axis of the elliptic convergence contour.

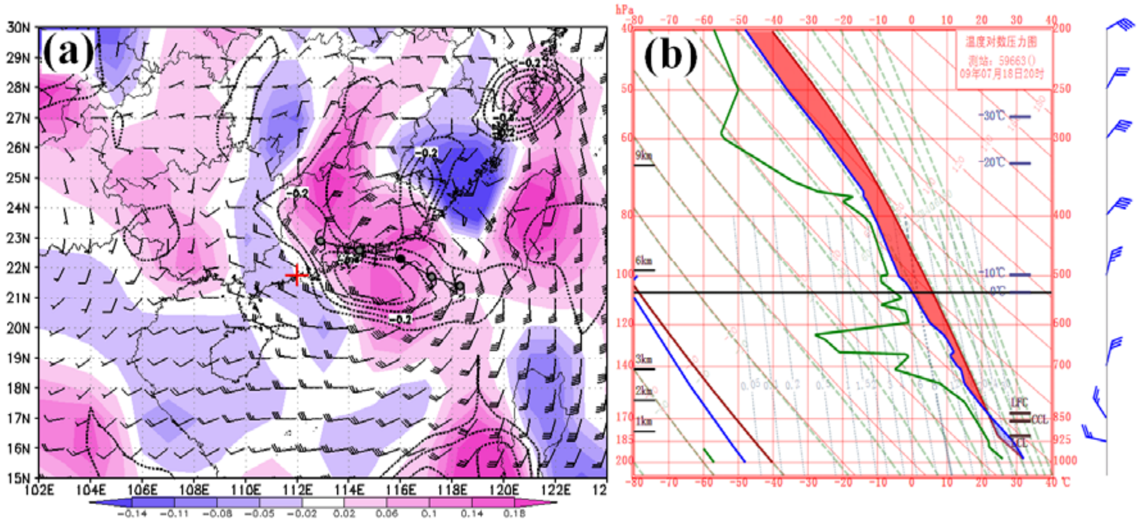

Figure 5. (a) Frontogenesis (10^{-9} K km^{-1} h^{-1}, warm color for positive, indicating frontogenesis, and cool color for negative, indicating frontolysis), and vertical velocity (black solid contour, Pa s^{-1}) and horizontal wind field at 925 hPa at 1200 UTC 18 July 2009. (b) the T-logP plot of a radiosonde in front of the convective line (located at the red "+" mark in (a)).

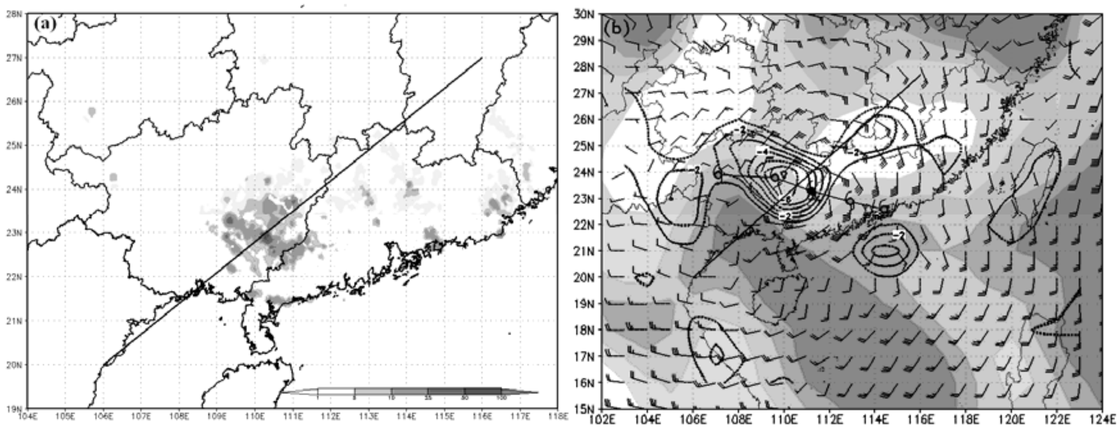

Figure 6. a: distribution of the actual rainfall from 0500 UTC to 0600 UTC 19 July 2009; b: distribution of the surface CAPE (shaded, unit: J kg^{-1}, the color bar is the same as in Figure 4a) and divergence at 850 hPa (dash line, the negative values show the convergence, unit: 10^{-5} s^{-1}) at 0600 UTC 19 July 2009.

The instability is indicated by not only large CAPE but also the vertical distribution of pseudo-equivalent potential temperature (θ_{se}). The vertical distribution of θ_{se} at 1200 UTC 18 July along the straight line segment in Figure 4c is shown in Figure 7a. This line crosses the area with large CAPE and convergence at 850 hPa. θ_{se} is low between 700-500 hPa in front of the convective line (to the left of the gray line in Figure 7a), which indicates that the θ_{se} shows a feature of dry and cold upper-levels and moist and warm lower-levels, which signifies apparent conditional instability. There are apparent low-level convergence and frontogenesis behind the convective line (on the right-hand side of the gray line in Figure 7a).

Figure 7a shows that the area with apparent low-level convergence is also the area with large frontogenesis. The frontogenesis contributes to the lifting that is very important to the formation of rainfall[7-9]. The contour of θ_{se} is basically normal to the land surface, which indicates neutral stratification during and after the occurrence of convection. This feature is helpful for the maintenance of the convection because when the environmental is conditionally unstable, the convergent disturbance associated with the approaching of the TC triggers the release of the unstable energy and thus the convection. As a result there appears neutral or stable stratification. The low-level convergence becomes the disturbance mechanism for the downstream convection. The downstream area of the developed convective line and convergence are still in an unstable state. The convergent disturbance and the convective line will continue to develop and intensify and move forward. Instability is also a necessary condition for the intensification of the convective line and convergent disturbance.

Concerning the conditions for the rainfall in Guangxi at 0600 UTC on July 19, the unstable area is located in front of the convective line. The area with strong convection and rainfall is featured by apparent low-level convergence and frontogenesis which almost overlap with each other. This result indicates that the influences from various dynamic factors are consistent with each other. This phenomenon is also consistent with the result of Gao et al.[9] in their analysis of the rainfall mechanism associated with tropical storm Bilis (2006).

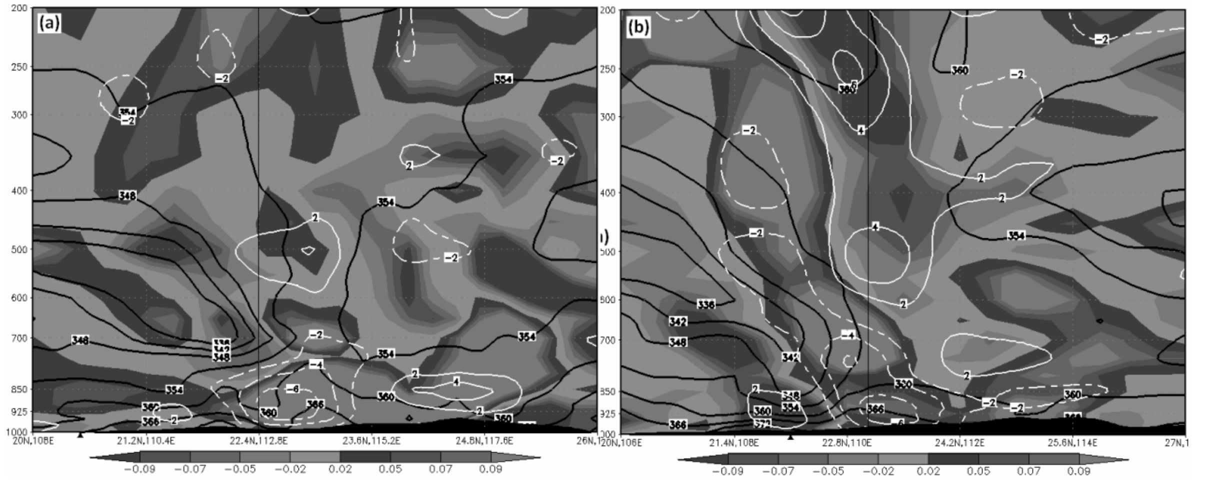

Figure 7. Vertical cross sections of the frontogenetical function (shaded, color changing to lighter shade inwards indicates frontogenesis while color changing to darker shade indicates frontolysis, unit: 10^{-9} K km^{-1} h^{-1}), pseudo-equivalent temperature (black line, unit: K) and divergence (white line, unit: 10^{-5} s^{-1}). The gray line shows the vertical line of the intersection of the profile and the strong rain belt. a: along 20°N, 108°E to 26°N, 120°E at 1200 UTC 18 July 2009 (the line is showed in Figure 4c); b: along 20°N, 106°E to 27°N, 116°E at 0600 UTC 19 July 2009 (the line is shown in Figure 5a or Figure 5b).

5 SUMMARY

The rainfall associated with Molave can be classified into two stages. The first stage is the rainfall in Guangdong. The second stage is the rainfall in Guangxi. The rainfall in the two stages shows a different location with respect to the TC track and thus could be caused by somewhat different mechanism. The rainfall in the first stage seems to be associated with the convection due to the dynamic lifting outside the tropical cyclone. The rainfall in the second stage is likely due to the dynamic lifting in the core area of the TC. This result indicates that the weakened TC tends to be associated with convection close to the TC center. It is discussed in detail as follows.

(1) The rainfall in Guangdong is associated with the convective line that appears in the front-right direction of the TC track. The convective line moves with the TC and turns anticlockwise around the TC center to the front and front-left of the TC track during its life cycle. The convective line swept most areas of the province. The convective rainfall in Guangxi appears to the front and front-left of the TC track and shows a similar anticlockwise turning around the TC center.

(2) The convection and heavy rainfall generally appear in the border between unstable and convergent area and is close to the convergent center. The unstable area is located in front of or downstream of the convection and convergent area. When the convergent disturbance is approaching, the unstable energy is released and thus the convection is developed.

(3) Low-level convergence is usually overlapped with frontogenesis. The stratification is stable or neutral in the area with strong convection indicating that most unstable energy has been released. What is important is that the low-level convergence is a mechanism that triggers the release of unstable energy in the downstream area of the convection.

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Citation: GAO Shuan-zhu and LV Xin-yan. Diagnostic analysis on the distribution of rainfall associated with typhoon “Molave” (0906). *J. Trop. Meteor.*, 2012, 18(2): 220-227.