Numerical Simulation and Moist Potential Vorticity Analysis of Torrential Rain in Jiangxi Province during June 2010

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Abstract Based on the conventional ground observational data, a numerical simulation and moist potential vorticity (MPV) analysis has been carried on heavy rainfall event over Jiangxi province from 19 June to 20 June 2010, with a meso-scale rainstorm model. The results show that this rare rainstorm is a typical heavy rainfall over Meiyu front. The cold air flow behind North China vortex joined up the southwestern flow located in the northwest part of the strong and stable subtropical high, thus the cold air and warm air converged and maintained over the northern part of Hunan and Jiangxi province. The simulated precipitation of the high resolution model is very similar to the observational rainfall. The model has a good predictive skill for the location, intensity and center of heavy rainfall. By moist potential vorticity analysis, it is found that the distribution characteristic of MPV which heavy rainfall happens ahead has an obvious indication for precipitation forecast. The vertical overlapping of the positive and negative MPV1 areas is favorable to the generation and development of rainstorm. This zone is also the conjoint area of convective instability and baroclinic instability.

Key words Torrential rain, Precipitation forecast, Numerical simulation, Moist potential vorticity

The Meiyu (or Baiu in Japan and Changma in Korea) front is the most important severe weather system in East Asia in summer. Meiyu front and the precipitation which it induced have always been the concern of meteorologist[1–9]. Since the β-scale convective storm is local, sudden and frequent, the formation mechanism issues of such precipitation have not been completely understood. From June 17 to 20, 2010, there was a rare continuous heavy rain in the central and northern Jiangxi since records began, and the strongest precipitation occurred on June 19. From 08:00 on June 19 to 08:00 on June 20 (Beijing time, the same as below), there was a heavy rain in multiple observatories of Jiangxi Province and Fujian Province, and torrential rain appeared in some observatories. The 24-h accumulated precipitation observed was 329 mm in Jinxian County of Jiangxi Province, and the 24-h accumulated precipitation observed was 278 mm in Nanchang County of Jiangxi Province. The rare heavy rainfall caused severe flooding in northern Jiangxi and breakdown of the Changkai dam in Fuzhou City[10], and 145000 people in five townships of Linchuan District were under serious threat. Yin Jie *et al.*[9] use WRF model for the numerical simulation of this process, and note that the β-scale vortex has a significant impact on this torrential rain. Wu Guoxiong *et al.*[11] prove that the frictionless adiabatic saturated moist air has the moist potential vorticity conservation features, and propose the theory of tilted vorticity development on this basis. Li Yaohui and Shou Shaowen[12] apply the theory of moist potential vorticity to analyze a Yangtze River – Huaihe storm process and point out that the moist potential vorticity distribution features well correspond to the storm weather systems caused by the lower troposphere. Jiang Yongqiang *et al.*[13] use the principle of conservation of moist potential vorticity to make analysis, and the results show that the absolute value of stability of lower convection decreases rapidly and the vertical vorticity undergoes a sharp increase, thereby forming the β-scale vortex. Gao Wanquan *et al.*[14] analyze the moist potential vorticity of one strong convective storm in North China, and it is found that the moist potential vorticity's configuration of "vertical supraposition of positive and negative zones" is a situation favorable to the formation of severe convective storm.

Whether the Meiyu front storm has the similar characteristics? So far, the research in this area is still rare.

In this study, we use the meso-scale rainstorm model (referred to as MRM)[4–7], for the numerical simulation and moist potential vorticity analysis of the torrential rain process in Jiangxi Province from June 19 to 20, 2010, to further explore the formation mechanism of the torrential rain, reveal the causes of torrential rain, and provide a reference for improving the storm forecasting skill. The horizontal calculation of the model was between 90° – 130°E and 15° – 50°N. The horizontal resolution of the model was 18 km. The initial field data of the model came from the daily use of ground and upper air data.

1 Numerical simulation of precipitation

1.1 Analysis of weather situation The storm process occurred under the combined effect of favorable large-scale circulation and weather systems. At 500 hPa, a stable vortex was maintained over North China from 20:00 on June 16 to 08:00 on June 19. The North China vortex slowly moved eastward during the storm

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process, and began to move into the sea at 20:00 on June 19. In the bottom of the North China vortex near 30° N, the multiple shortwave trough moved eastward, and the cold advection behind the trough led the cold air flow to move southward to the middle and lower reaches of Yangtze River, providing cold air source.

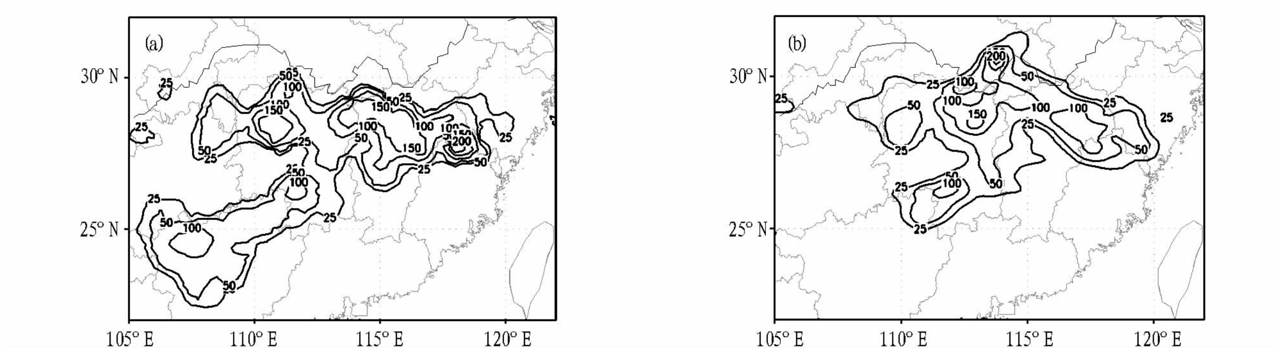
Meanwhile, the West Pacific subtropical high was extended from the central Pacific to Indo – China Peninsula, showing the belt distribution. It was strong and stable, and the subtropical high ridge line was located near 20° N. The strong southwest air flow prevailed in the north of subtropical high, and the warm and humid air flow transported the water vapor to the northern part of Hunan and Jiangxi provinces. The low-level shear line was maintained in the central and northern Jiangnan, and the storm zone was located near the shear line. There was a southwest vortex noticeably moving eastward at the 700 hPa and 850 hPa lower troposphere.

At 20:00 on June 18, the southwest vortex center was located in western Guizhou Province, and the warm shear was located in the northern part of Guizhou Province and Hunan Province. At 08:00 on June 19, the southwest vortex further moved eastward, and the center was located in the northern part of Chongqing City and Guizhou Province. The shear line was maintained, the southwest low-level jet flow was increased, and at the same time, the north cold air flow was strengthened. At 20:00 on June 19, the strong southwest warm and humid air flow was maintained, and the north cold air flow moved southward, so the cold air met the warm air, and the vortex moved eastward to the eastern part of Hunan Province. At 08:00 on June 20, the vortex moved in Jiangxi Province, and the southwest low-level jet flow was strong, leading to 20 m/s southwest wind. Then the vortex gradually moved eastward to the sea, and the heavy rainfall weakened.

1.2 Simulation and analysis of precipitation The distribution of 24-h observed cumulative ground precipitation and the simulated precipitation is shown in Fig. 1. From Fig. 1, it can be seen that the rain belt distribution simulated by MRM is basically similar to the precipitation in Hunan Province and Jiangxi Province, and the model can better simulate the location, intensity and center of storm.

To objectively and quantitatively test the forecast effect of precipitation level, we carry out the TS score statistical test on the 24-h cumulative precipitation according to five levels [drizzle or above (≥1 mm); moderate rain or above (≥ 10 mm); heavy rain or above (≥ 25 mm); rain storm or above (≥ 50 mm); torrential rain storm or above (≥ 100 mm)][6-7]. TS value of drizzle is 0.70; TS value of rain storm is 0.45; TS value of torrential storm is 0.22.

The simulated storm center in individual places deviates from the actual precipitation center, but in terms of precipitation belt distribution, precipitation intensity forecast and TS score statistical test, MRM exhibits better forecasting capability during this storm process.



Note: a, observed precipitation; b, simulated precipitation, unit: mm.

Fig. 1 The distribution of 24-h observed cumulative ground precipitation and the simulated precipitation

2 Moist potential vorticity analysis

2.1 Horizontal distribution of moist potential vorticity In p coordinate system, the moist potential vorticity is defined as follows:

$$MPV = -g(fK + \nabla_p \times V) \cdot \nabla_p \theta_{se} \quad (1)$$

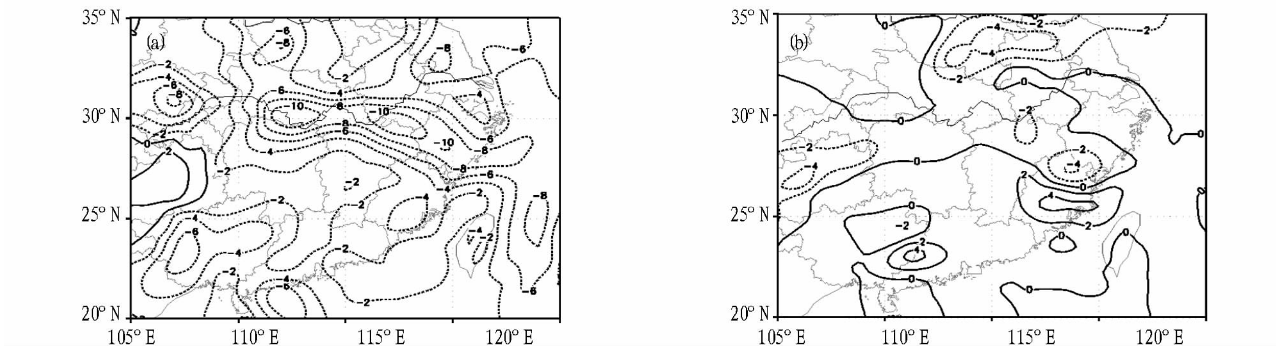
Given that the horizontal change in the atmospheric vertical velocity is much smaller than the vertical shear of the horizontal velocity, when ignoring the horizontal change in vertical velocity, it is written in component form, then:

$$MPV1 = -g(\xi_p + f)\frac{\partial \theta_{se}}{\partial p} \quad (2)$$

$$MPV2 = g\frac{\partial v}{\partial p}\frac{\partial \theta_{se}}{\partial x} - \frac{\partial u}{\partial p}\frac{\partial \theta_{se}}{\partial y} \quad (3)$$

In formula (2), MPV1 is the vertical component of moist potential vorticity (positive pressure term), whose value depends on the product of the vertical component of absolute air vorticity and the vertical gradient of equivalent potential temperature (ξ_p is the vertical vorticity; f is the geostrophic vorticity; θ_{se} is the pseudo-equivalent potential temperature). Since the value of absolute vorticity is positive, when the atmosphere is unstable convection, then $\frac{\partial \theta_{se}}{\partial p} > 0$, MPV1 < 0; when the atmosphere is stable convection, then $\frac{\partial \theta_{se}}{\partial p} < 0$, MPV1 > 0.

In formula (3), MPV2 is the horizontal component of moist potential vorticity (baroclinic term), whose value is determined by the vertical shear (horizontal vorticity) of wind and the horizontal gradient of θ_{se}, characterizing the atmospheric wet baroclinity. The unit of moist potential vorticity is PVU, $1PVU = 10^{-6} m^2 \cdot s^{-1} \cdot K \cdot kg^{-1}$.



Note: a, MPV1; b, MPV2, unit: PVU.

Fig. 2 Horizontal distribution of MPV1 and MPV2 at 850 hPa

The horizontal distribution of field moist potential vorticity component on 08:00, June 19, 2010 is objectively analyzed (Fig. 2). As can be seen from Fig. 2, MPV1 is negative at 850 hPa isobaric surface in the whole precipitation region, indicating that the lower atmosphere is unstable convection, and near Yueyang City of Hunan Province and Jiujiang City of Jiangxi Province, there are two centers with negative value of MPV1 less than −10PVU. The torrential rain mainly occurs near the dense contour area in the southern negative value center of MPV1, where the cold air meets warm air, conducive to moisture convergence, and dramatic development of vertical vorticity, thereby leading to the strong development of mesoscale convective system. The distribution of MPV1 at 850 hPa plays a good indicative role for the heavy precipitation area.

The heavy precipitation occurs mainly near the negative value area of MPV2 and the zero line, indicating that there is weak atmospheric wet baroclinity in the lower atmosphere, which is closely related to the characteristics of Meiyu front. The absolute value of MPV1 is obviously larger than that of MPV2, and the distribution of MPV1 roughly represents the distribution of MPV. The northern storm area is the strong negative value area of moist potential vorticity, and the south is the weak negative value area of moist potential vorticity.

The torrential rain occurs mainly in the weak negative value area of MPV. The positive pressure term and baroclinic term of moist potential vorticity reflect the convective instability of atmosphere, symmetric instability and baroclinic instability. This strong convective storm occurs mainly in the location with convective instability and baroclinic instability, which is different from the case study results of the North China storm[14].

2.2 Spatial-temporal evolution of MPV1 and θ_{se} The spatial-temporal evolution of MPV1 and θ_{se} near Nanchang City (28.7°N, 116°E) from 08:00 June 19, to 08:00 June 20, 2010, can be shown in Fig. 3. It can be seen from Fig. 3 a that in the region where torrential rain occurred from 08:00 June 19 to 03:00 June 20, the value of MPV1 is negative under 600 hPa, and −4PVU negative value center is formed near 800 hPa, indicating that the lower troposphere convective instability is enhanced near Nanchang City.

Meanwhile, except −2PVU negative value center near 200 hPa from 12:00 to 14:00, June 19 for the MPV1 above 500 hPa, others are all positive value areas. The high potential vorticity area stretches down from the stratosphere in the shape of funnel, and a large value center near 300 hPa reaches 8 PVU, showing that the upper troposphere is the stable convective region, and the cold air flow sweeps down in the form of high − value potential vorticity column.

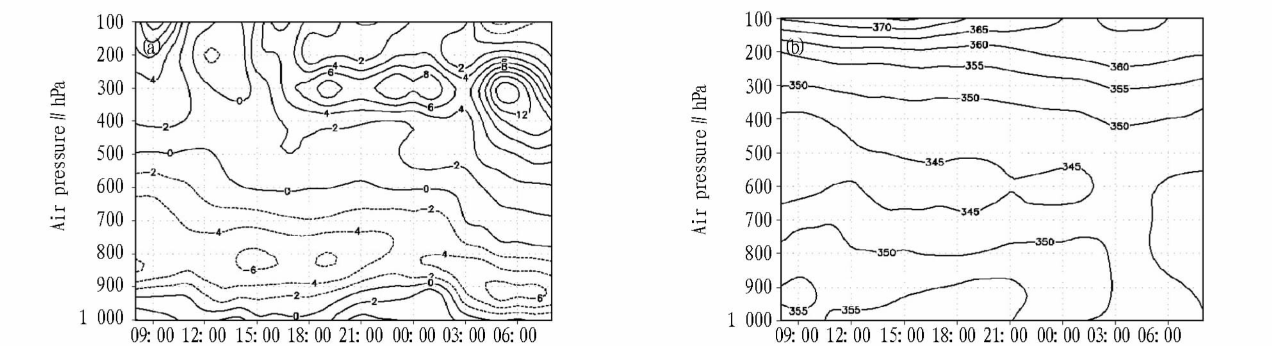
After 03:00 June 20, the southwest vortex moved eastward and the cold air flow swept down, so the high potential vorticity area stretched down from the stratosphere in the shape of funnel, forming a large value center near the 300 hPa layer (14 PVU), and the high potential vorticity tongue was extended to 700 hPa. There is atmospheric baroclinity, weak convective instability and high-level positive potential vorticity, very conducive to the growth of vertical vorticity, in line with the vorticity growth theory.

The above analysis shows that the distribution of moist potential vorticity plays a strong indicative role for the occurrence of severe convective storm and precipitation area. The configuration situation of MPV1 (vertical stacking of positive and negative areas) is conducive to the occurrence and development of strong convective storm. In order to further reveal the precipitation mechanism of this strong convective storm, the time evolution figure of is drawn near the center of the heavy precipitation (Fig. 3b). There is a low value area of near 400 − 700 hPa over the storm area, indicating that there is cold air flow intruding from the middle.

At 03:00, June 20, when the contour of shows vertical distribution, in the intersection of cold and warm air, the vertical gradient of is close to zero, the atmospheric baroclinicity is increased, and the vertical stability is close to zero. The warm and humid air rises along near the front. According to the principle of conservation of MPV[11], the reduced vertical gradient of will inevitably lead to sharp increase in the vertical vorticity, to keep moist potential vorticity conserved.

The increasing vertical vorticity enhances the vertical speed.

Due to the rapid development of vertical vorticity, the strong convection occurs, conducive to the occurrence or reinforcement of heavy precipitation. The moist potential vorticity theory well explains the formation mechanism of this torrential rain, which is of important significance to the future forecasting of Meiyu front storm.



Note: a, MPV1, unit: PVU; b, θ_{se}, unit: K.

Fig. 3 The simulated spatial-temporal evolution of MPV1 and near Nanchang City (28.7°N, 116°E) at 08:00, June 19, 2010

3 Conclusions

In this paper, we carry out the numerical simulation of a torrential rain process in Jiangxi Province, to study the ability of MRM to simulate the storm process. According to numerical simulation and the moist potential vorticity analysis, the results show that the torrential rain is a typical Meiyu storm, and the cold advection after North China vortex and strong southwest air flow in the northwest of subtropical high, making the Meiyu front stable in the northern part of Hunan and Jiangxi province. The rainfall field simulation results of meso-scale rainstorm model are close to the observations, and this model well simulates the location, intensity and center of storm. The distribution of MPV and MPV1 at 850 hPa corresponds to the storm area. The northern storm area is the strong negative value area of moist potential vorticity, and the south is the weak negative value area of moist potential vorticity. The torrential rain occurs mainly in the weak negative value area of MPV. The distribution of moist potential vorticity plays a strong indicative role for the occurrence of severe convective storm and precipitation area.

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