Study on Moist Potential Vorticity and Symmetric Instability during a Heavy Rain Event Occurred in the Jiang–Huai Valleys①

Shou Shaowen (寿绍文) and Li Yaohui (李耀辉)②

Nanjing Institute of Meteorology, Nanjing 210044

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ABSTRACT

In the light of the theory on moist potential vorticity (MPV) investigation was undertaken of the 700 hPa vertical (horizontal) component MP1 (MPV2) for the heavy rain event occurring in July 5–6, 1991. Results show that the distribution features of the two components were closely related to the development of a mesoscale cyclone as a rainstorm–causing weather system in the lower troposphere in such a way that the ambient atmosphere of which MPV1 > 0 and MPV2 < 0 with $|MPV1| \geqslant |MPV2|$ favored the genesis of conditional symmetric instability (CSI) and that, as indicated by calculations, a CSI sector was really existent in the lower troposphere during the heavy rain happening and contributed greatly to its development.

Key words: Heavy rain, Moist potential vorticity (MPV), Conditional symmetric instability

1. Introduction

Subsequent to the 1970s, many native meteorological researchers discovered that meso–scale symmetric instability disturbance is likely to play an important role in triggering and organizing banded convection and responsible directly for multiple rain–bands. As a highly effective technique for the genesis causes and dynamic research of mesoscale systems, potential vorticity theory was proposed and improved.

Ertel (1942) developed a concept of isentropic potential vorticity (IPV) that is of great importance in the scope of synoptic research, indicating that in an adiabatic, frictionless process, the IPV is a conservative quantity. Based on intensive research of potential vorticity theory and more complete summary of previous studies, Hoskins (1974, 1985) showed that if non–adiabatic heating and frictional effects are ignored, isobaric potential vorticity (PV for short) and MPV in rainfall occurring are conservative, i.e., for negative MPV, CSI is likely to take place and that upper tropospheric or stratospheric potential vorticity can travel downward, exerting effect on the development of cyclones in the lower troposphere and near–surface layer. In virtue of PV properties, meteorological researchers have made numerous efforts at atmospheric, and particularly mesoscale phenomena, arriving at a range of noteworthy conclusions. Sheng (1984) reported his PV study of the heavy rain event in July 1981,

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②Current affiliation: Lanzhou Drought Research Institute, Meteorological Bureau of Gansu Province.

indicated that the greater local variation of equivalent PV denoted a source of energy for small- and meso-scale systems, serving as an important indicator of strong convective weather on a local basis. Qin (1989) made a study of the relation between quasi-geostrophic potential vorticity (GPV) and banded precipitation, demonstrating that the rainfall fell from a single and multiple rainbands, alongside with their formation / maintenance mechanisms. Lu and Ding et al. (1994) showed that in May-July 1991, the high PV cold air coming from the north and northeast interacted with the southern warm air, thus sustaining a Meiyu front for the prolonged rainstorm over the Jiang-Huai valleys. Wu, Cai and Tang (1996) proposed a concept of 'slantwise vorticity development' for an parcel moving over an isentropic surface in relation to vertical vorticity development based on detailed theoretical study on IPV.

In May to July, 1991, the Jiang-Huai reaches were hit by serious rainstorms and floods on a large scale and the rainfall event on July 5-6 was associated with the interaction of upper-air cold air with a lower -level mesoscale vortex and a mesoscale surface cyclone, thus making the rainstorm typical of Meiyu front origin, and the meso systems played a critical part in the event. This paper presents the analysis of the genesis / development of the torrential rain event in terms of the PV and CSI principles.

2. Data source and weather features

2.1 *Data source*

Employed are the global gridded data taken twice-daily at 0800 and 2000 BST (Beijing Standard Time) as initial values prediction from the System of Global Data Assimilation for Medium-range numerical Prediction Division of National Meteorological Center of China. Were assimilated these datasets, consisting of nonconventional sounding, satellite and radar measurements, thus containing richer practical mesoscale information, they have horizontal 2.5° × 2.5° resolution and contain isobaric surface height, temperature, u- and v-wind components at 100, 200, 300, 500, 700, 850 and 1000 hPa, relative humidity at 300, 400, 500, 600, 700, 850 and 1000 hPa and sea-level pressure, the domain covers 12.5°-62.5°N, 87.5°-142.5°E, and the 7-level u- and v- wind components were subjected to interpolation to 14 levels by the Lagrangian scheme (100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 950 and 1000 hPa) for diagnostic calculation.

2.2 *Space / time distribution of the rainstorm*

This rainfall event occurred from 2000 BST, July 5 till 2100 of the next day, covering mainly the provinces of Hubei, Henan, Anhui and Jiangsu with torrential rain or strong rainstorm striking more than one area in this region (data being mostly the hourly station measurements, which were then interpolated to square grids), with maximum daily precipitation in excess of 200 mm (Fig.1).

The distribution of rainfall at a 3-h interval for 24 hours starting from 2000 BST, July 5, showed that at 2000 BST of the day, an isolated fallout region emerged in central Henan that was extending eastward and the rainfall center moving, too, in this direction, reaching maximum increase of precipitation at 0800 BST, July 6 and measuring maximum 3-h rainfall of 65 mm at 1100 BST on the day. Robust rain cluster moved faster (slowly) along the eastern (western) boundary of the rain sector and the rain cluster was travelling east by north between the Changjiang and Huaihe River basins of eastern China under the guidance of steering flow at 2000 BST, July 6, an intense rainstorm belt appeared with the central value of 40 mm / 3 h

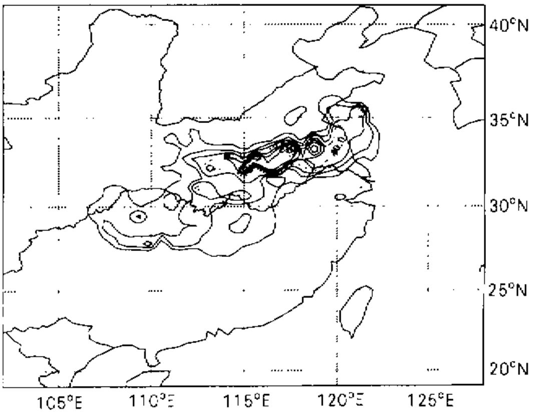


Fig. 1. Measured total rainfall (mm, contoured at 20.0 mm) in the period from 2000 BST, July 5 to 2000, July 6, 1991.

in the coastal belt of north Jiangsu and a weak rainband in north Guizhou. Therefore, a nearly E–W directed rainbelt stretched in the mid–lower reaches of the Changjiang River, based on the 24–h total rainfall.

2.3 *Low–level circulation*

The most significant circulation feature at 850 hPa typically for the low level was a meso vortex as a system responsible directly for the rainfall. At 0800 BST, July 5, the vortex genesis occurred in the Sichuan basin and began to move eastward and strengthen, 24 hours later, its center was between Zhengzhou and Hankou, the cyclonic circulation became strong enough with the SW wind in its southeast part enhanced greatly, afterward the vortex began weakening and was over the Korean Peninsula at 0800 BST, July 6, leaving East China under the control of a high that followed (Fig.2).

Accordingly, at 1400 BST, July 5, a SW vortex came into being on the east by north side of the Sichuan basin and began to move east, entering Anhui Province at 0800–1400 BST the following day, during which time it was greatly intensified with its cyclonic circulation well–displayed and minimum pressure reaching 947 hPa, and the E–W directed shear line entrenched between the Changjiang and Huaihe Rivers in East China, forming a typical Jiang–Huai cyclone.

We can see that the rainfall intensity increased considerably (as seen from the rainfall at 0800 BST, July 6 and 1100 BST, the next day) concurrently with or shortly after the depending of the 700 and 850 hPa vortices and reinforecement of the surface cyclone. We thus come to the conclusion that a meso vortex generated in the lower troposphere and enhanced in its eastward motion causes the disturbance on the surface cold front to develop dramatically, leading to cyclonic waves which are responsible for a surface cyclone that produces an intense rainstorm event. In our study, evidently, the meso low–level vortex with its related surface cyclone is responsible for the unique system for the torrential rain.

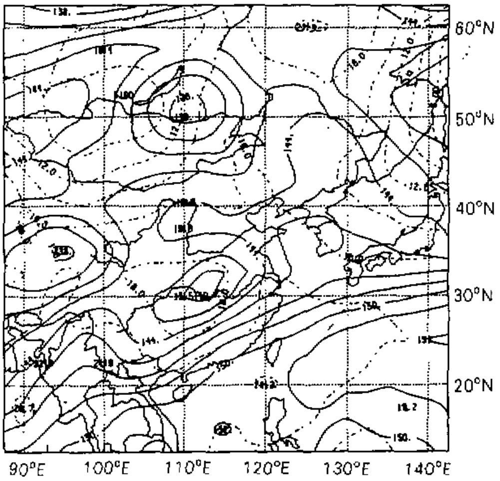


Fig. 2. 850 hPa circulation pattern at 0800 BST, July 6, 1991 where solid (dashed) line denotes the isohypse (constant humidity line).

3. MPV Analysis

3.1 *MPV theory*

When static approximation is introduced into adiabatic, frictionless atmosphere, the MPV *in the P coordinate system is expressed as*

$$MPV = -g(f\cdot\vec{k} + \nabla_p \times \vec{V})\cdot \nabla_e \theta_e = constant \tag{1}$$

where $\nabla_p = \frac{\partial}{\partial x}\vec{i} + \frac{\partial}{\partial y}\vec{j} + \frac{\partial}{\partial p}\vec{k}$ denotes the three–dimensional gradient operator. Assuming *that the horizontal change in vertical velocity is small enough to be ignored, we put* (1) *into* the form

$$MPV \approx -g(\zeta + f)\frac{\partial\theta_e}{\partial p} + g(\frac{\partial v}{\partial p}\frac{\partial\theta_e}{\partial x} - \frac{\partial u}{\partial p}\frac{\partial\theta_e}{\partial y}) \tag{2}$$

With $\zeta = (\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$ stands for the vertical velocity in the P coordinate. By defining the first (second) term on the rhs of (2) to be the MPV vertical (horizontal) component, we find

$$MPV1 = -g(\zeta + f)\frac{\partial\theta_e}{\partial p}$$

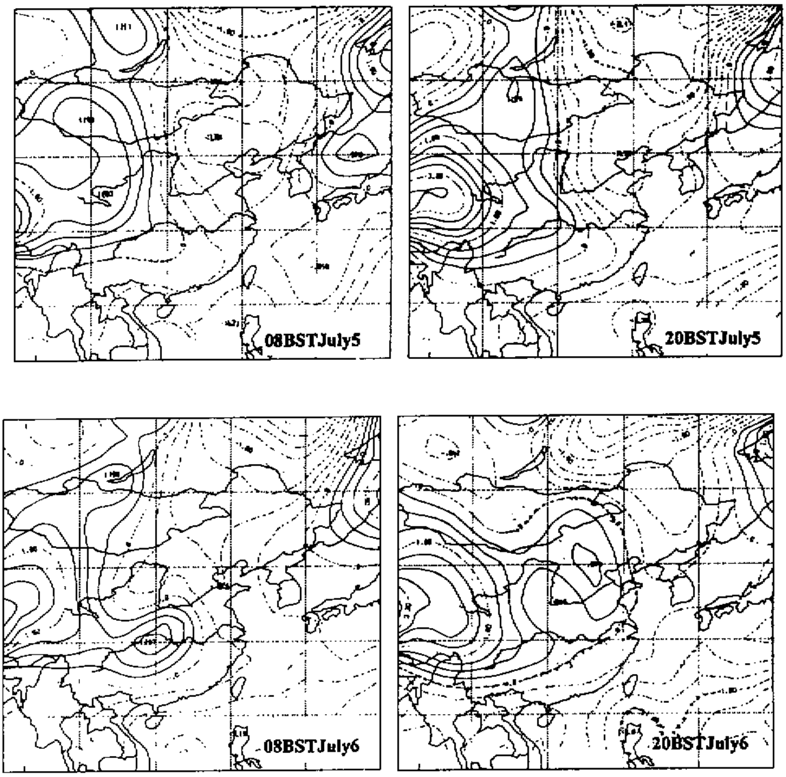
$$MPV2 = g(\frac{\partial v}{\partial p}\frac{\partial\theta_e}{\partial x} - \frac{\partial u}{\partial p}\frac{\partial\theta_e}{\partial y}) \tag{3}$$

Suggesting that MPV1 is a moist barotropical term for the role or inertial stability ($f+\zeta$) and convective stability $(-g\frac{\partial\theta_e}{\partial p})$, and MPV2 is a moist baroclinic term containing the contribution of moist baroclinicity ($\nabla_p \theta_e$) and vertical shear of horizontal wind.

3.2 *MPV features and environmental atmospheric conditions*

We now proceed to deal with MPV1 and MPV2 on the 850 hPa surface from 0800 BST, July 5 to the same hour of the next day, shown in Figs.3a and 3b, respectively. Fig.3a (for MPV1 at 0800 BST, July 5) depicts that a positive (negative) MPV1 region was to the west (east) of 110°E, indicating the activity of cold air (warm, moist air and anticyclonic circulation); one positive center of MPV1 appeared in 100°–110°E north of 50°N and another in 30°–40°N, 100°–110°E, the latter being stronger; at 2000 BST, July 5, the 30°–40°N center was greatly enhanced with its value increased from 0.24 to 0.36 PVU and extending eastward; with the intensity growing, rainfall happened; at 0800 BST, July 6, a closed center of 0.17 PVU emerged in 30°N, 110°E and would have been just where the vortex center was below 700 hPa if it had been moved slightly east; after 2000 BST, July 6, the closed center was reduced in vigor and moved northeast to the west side of the Bohai Sea; concurrently, the western boundary of the positive MPV1 region began to withdraw westward; a new center came into being in West China at 0800 BST, July 7.

From the MPV2 plot (Fig.3b) one sees that at 0800 BST, July 5, in addition to negative



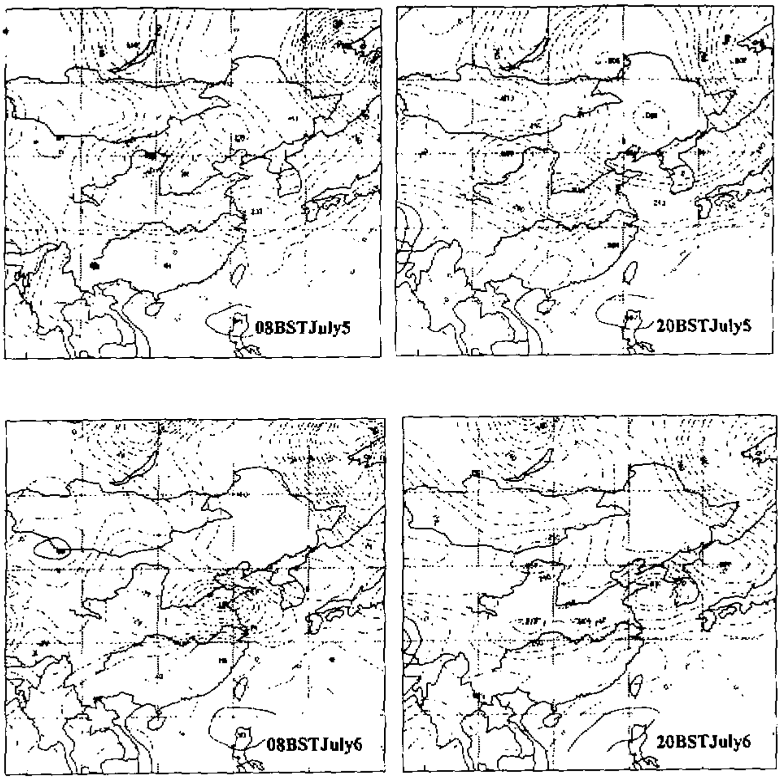


Fig. 3. 700-hPa MPV1 and MPV2 distribution in the period from 0800 BST, July 5 to 2000 BST July 6, 1991. (a) MPV1; (b) MPV2.

centers related to the positive counterparts, respectively in NW China and 100°-110°E north of 50°N, a quite strong negative center was located in the Changjiang - Huaihe River basins, and weakened dramatically and disappeared at 0800 BST,July 6, one negative center was to the west of the Great Bend of the Huanghe River(~ 40°N, 110°E) and another around Xiangyang (32°N, 102°E), the latter corresponding in position to the positive counterpart in the same period; afterwards, the negative center in the Changjiang - Huaihe region at 2000 BST, July 6 in close relation to the rainstorm's center.

Based on the analysis of the Changjiang-Huaihe River rainstorm event for 2000 BST, July 5 to 2100, July 6, 1991, we find the 700 hPa MPV to be of note as follows:

1) The positive MPV1 and negative MPV2 regions had their evolution / development in roughly agreement with those of the lower-troposphere weather system, i.e., meso-vortex, with the negative MPV2 center even more closely associated with the system in the evolution. From 2000 BST, July 5 to 0800 BST of the next day, the two components experienced greater development, leading to drastic augment of rainfall at 0800 BST, July 6, yielding maximum 3-h precipitation measured at 1100 BST of the day, suggesting the crucial role of MPV in the rainstorm enhancement.

2) During the eastward migration of the MPV1 / MPV2 systems, the positive MPV1 system got increasingly weak as a function of time, as opposed to the negative MPV2. By and large, particularly prior to 0800BST, July 6, $|MPV1| \geqslant |MPV2|$, implying the predominant role of inertial stability $(f+\zeta) > 0$ and convective (static) stability $(N_m > 0)$.

3) Dominant was the contribution of convective (static) stability to the MPV1 that weakened due primarily to the decrease of convective stability. Since that low-level jetstream is greatly at 700 hPa leads to the vertical shear of windspeed $(\frac{\partial U}{\partial p} < 0)$, the wind shear and baroclinicity made negative-value contribution to the MPV2 which was then intensified owing dominantly to the increase in baroclinicity.

4) The negative MPV2 region always took a band form to the north of 30°N with isopleths close together around the latitude, indicating that the baroclinicity, especially its meridional component $(\frac{\partial \theta_e}{\partial y} > 0)$, was quite intense.

4. Symmetric instability and MPV

Symmetric instability (SI) denotes a kind of meso motion developed when the environmental atmospheric stratification is stable or neutral with inertial stability available. Quantitatively, air parcel experiences slantwise ascent for SI when the constant M (absolute

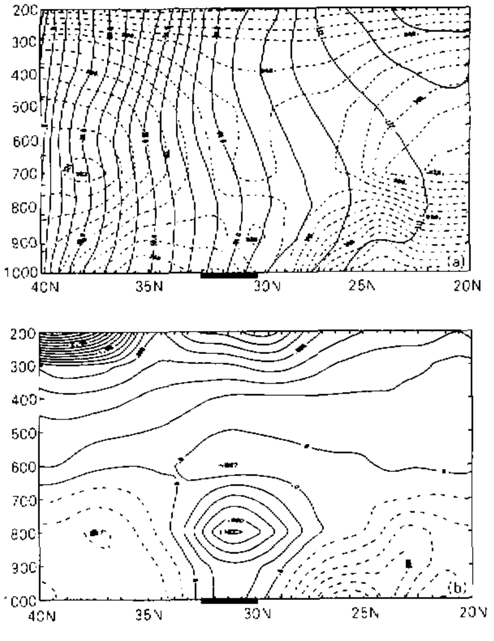


Fig. 4. (a) 116.2°E meridional section of model-calculated constant M_g (thin full line) and constant θ_e (thin dashed line) for 0800 BST, July 6. (The thick bar below denotes the latitudes of the hyetal region.); (b) as in Fig.4a except for MPV.

momentum) surface declines to less extent than does the constant potential temperature surface (Shou, 1993). From the foregoing analysis of isobaric MPV we see that the mid-lower troposphere as the environmental atmosphere over the rainstorm band was roughly in a state of inertial stability ($f+\zeta>0$), and convective (static) stability ($N_m > 0$) or weak instability, accompanied by stronger baroclinicity. Now, a problem arises whether SI comes into play in such an environment. For moist air the SI criterion takes the form

$$Ri < f/\zeta_a, \tag{4}$$

where Ri stands for the Richardson number and ζ_a for absolute vorticity. As shown in Hoskins (1974), MPV < 0 represents a necessary condition in judging conditional SI related to banded rainfall as well. Here we present the calculations of absolute geostrophic momentum $M_g (M_g = u_g - fy)$ and the meridional cross-section of constant M_g and θ_e surface through the rainfall center (Fig.4a), revealing that at 0800 BST, July 6 between 800-500 hPa there arose SI with the slop of the constant M_g surface smaller compared to that of the constant θ_e surface but at other observing times the SI was found weaker, the stratification in the SI region was weakly stable or neutral and related to a negative center on the MPV section (Fig.4b), thus demonstrating that SI did happen in this rainstorm event and maximum rainfall occurred 3 h after (i.e., at 1100BST, July 6). As an important mechanism for the vigorous rainstorm, therefore, the SI played an active role in this event.

5. Concluding remarks

From the definition we know that MPV contains in itself dynamical and thermodynamical properties and is applicable to the description of an environmental atmosphere in an even more precise manner. In the rainstorm, MPV1 > 0, MPV2 < 0 and $|MPV1| > |PMV2|$, indicating that the environmental atmosphere was in a weakly steady stratification and inertial stability in favor of SI development and our calculations do reveal that SI played an important role in the genesis / development of the rainfall and its related mesoscale systems.

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