DYNAMIC STUDY ON INFLUENCE OF INERTIAL GRAVITY WAVES INDUCED BY UNBALANCED FLOW ON MEIYU FRONT HEAVY RAIN*

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ABSTRACT

The Meiyu front heavy rain process in 1—3 June 2000 is numerically simulated in this paper, and results are then analyzed to show the effects of geostrophic balance collapse, unbalanced flow occurrence, low level jet (LLJ) development, and gravity waves genesis and propagation on the rainstorm. Analyses indicate that the sudden northwest movement of subtropical high may destruct the local geostrophic balance, leading to an increase in the local pressure gradient and the occurrence of ageostrophic flow, and meanwhile the adjustment of circulation starts to build a new balance. During the process, an LLJ and gravity waves appear correspondingly. The dispersion of unbalanced energy through the divergence/convergence of the geostrophic departure winds, promotes the propagation of strong wind cores along the LLJ, and the dispersion direction is influenced by the steering flow and the moisture concentration area. The development of LLJ is one of important conditions, which induces the heavy rain especially in the left front part of the jet where the convergence and shear of winds occur. It is also found that the genesis of disturbance, meso-vortex, and meso-convective system provides a favorable condition for the rainstorm. The above results are clearly illustrated by the high spatial and temporal resolution simulation data from a mesoscale numerical model.

Key words: Meiyu front heavy rain, unbalanced flow, low-level jet(LLJ), gravity waves

I. INTRODUCTION

The Meiyu front heavy rain is one of major meteorological disasters in China, and it brought about many times of devastated floods in the Changjiang-Huaihe River Valley in the past. Synoptic analyses suggest that during Meiyu front heavy rain processes, the concentration of a large mount of water vapor is frequently associated with a southeast LLJ, and its formation is companied with the large-scale circulation adjustment. Such an adjustment can be analyzed from multiple angles, however the mutual adjustment between wind and pressure fields is most fundamental. That is to say, after the geostrophic balance is broken down, the occurrence of ageostrophic wind will trigger inertial gravity waves. Along with the dispersion of the inertial gravity waves and the vanishing of the ageostrophic component of motion, the geostrophic relation between wind and pressure

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fields will be reestablished. The geostrophic adjustment theory was initially presented by Rossby (1937, 1938). Afterwards many researchers did many studies. For example, Cahn (1945) and Charney (1947) explained the effect of inertial gravity waves in the adjustment process. Yeh (1957) first pointed out the problem of scale in the geostropheric adjustment process. As far as the application of geostropheric adjustment theory is concerned, by using a two-dimensional model Fritts and Luo (1992) discussed features of gravity waves near a jet triggered in the geostrophic adjustment process, and pointed out that the ageostrophic motion near a jet is an important source of inertial gravity waves. Stobie et al. (1979) analyzed a violent storm process in May 1979 in the central United States, and found that the distribution and movement of storm are clearly associated with gravity waves. Uccellini and Koch (1982) investigated 13 cases of gravity waves, and their results show that the intensity and distribution of precipitation are affected by the waves.

In the recent years, the development of mesoscale meteorology, especially the advance in mesoscale numerical models provides a favorable condition for studies on the excitation and propagation of gravity waves after the occurrence of ageostrophic motion in Meiyu front heavy rain processes. In terms of the diagnostic analyses of the mesoscale numerical simulations of a Meiyu front heavy rain process, this paper reveals the effect of unbalanced flow and gravity wave dispersion on the formation of LLJ and the occurrence of heavy rain after the adjustment of the large-scale circulation.

II. DATA

The main data used include the NCEP global reanalysis data of $1^\circ \times 1^\circ$ resolution and at time intervals of 6 h, the mesoscale numerical simulation data, the Japanese GMS satellite cloud picture data, the observational data from the Chinese primary meteorological station network, and the hourly intensive observation rainfall. The highest horizontal resolution of the simulated data is 9 km, vertically at 23 layers by the NCAR/PSU non-hydrostatic model MM5 (third version).

III. HEAVY RAIN PROCESS AND ITS NUMERICAL SIMULATION

In June 2000, the major rain belt appeared in the Huaihe River Basin. Under the joint influence of a strong warm/moist southwest flow and a southward cold air, a successive torrential rain process took place in the period of 1—3 June (Fig. 1).

It can be seen from Fig. 1a that there were three areas of precipitation with the rainfall greater than 50 mm in the Changjiang-Huaihe River Basin from 0800 BT 1 to 0800 BT 2 June. In 0800 BT 2 to 0800 BT 3 June, the rain belt moved northwards, expanded its area, and an exceptional torrential rain of more than 100 mm occurred in the zonal area from the north of the Huaihe River to the east of Henan Province. The overall rainfall of the precipitation process was about 50—100 mm, and it exceeded 200 mm over parts of central Jiangsu, central and north Anhui, south Henan, and northeast Hubei Provinces. The total process rainfall at 62 stations in Henan Province exceeded the historical maximum in the same period, and the rainfall of the first two days in the north of the Huaihe River was 3—4 times the mean precipitation value in the first dekad of June.

It is seen from the 500 hPa chart at 2000 BT 31 May 2000 that the trough along the east coast of China shrank northwards as well as moved eastwards, and the subtropical high in the southeast of Taiwan started to stretch westwards and advance northwards, with the 588 dagpm contour expanding towards the southeast coast of China mainland. By

2000 BT 1 June, the subtropical high had completed the westward-stretching-northward-jumping. Correspondingly the 588 dagpm contour originally near east of Taiwan had moved to the vicinity of the Hainan Island as well as advanced northwards for 2—3 degrees in latitudes, and its domain had covered the most part of southern China coast (Fig. 2). The movement of the subtropical high established a favorable condition for subsequent precipitation over the Changjiang-Huaihe River Valley.

With strengthening of the subtropical high, a flow along its west fringe transferred warm/moist air northwards, and at the same time a weak cold air from northern China moved southwards, resulting in the formation of a Meiyu front over the Changjiang-Huaihe River Valley. Along with the genesis, strengthening, and eastward movement of a low vortex on the Meiyu front, heavy rain also started.

The heavy rain process is numerically simulated in this paper with the aid of MM5 model, and the simulated rainfalls are given in Fig. 3. The area and intensity of precipitation simulated are in generally agreement with the observations, which provides a basis for the following diagnoses of the process.

Figure 4a gives the simulated 700 hPa streamline field at 1000 BT 1 June 2000, and it can be clearly seen from the figure that there is a distinct southwest LLJ from the south of the Changjiang River, the west of South China, to the Changjiang River Basin. Figure 4b is the corresponding isotach field of Fig. 4a, and the intensity of the jet is greater than 16 m/s. The appearance of the LLJ plays an important role in the Meiyu front heavy rain process during 1—3 June, such as effects on the concentration and convergence of water vapor, the establishment and enhancement of vorticity and convergence fields, the vertical circulations, etc. The genesis of LLJ is closely related with the northward jump of the subtropical high, and thus a result of large-scale flow field adjustment.

IV. SUDDEN WESTWARD-STRETCHING-NORTHWARD-JUMPING OF SUBTROPICAL HIGH AND THE BREAKING OF GEOSTROPHIC BALANCE

Along with the westward-stretching-northward-jumping of the subtropical high, the 588 dagpm contour characterizing the ridge of the subtropical high on 500 hPa has moved to the vicinity of 25°N, 110°E in the afternoon to nighttime on 1 January, and the anticyclonic curvature of the contour also clearly increases (Fig. 2b). The sudden westward-stretching-northward-jumping of the subtropical high is first displayed by the allobars or changes in pressure gradients on large-scale pressure fields. Viewed from the westward stretching of the subtropical high, the place where the anticyclonic curvature of the ridge-line of the high is maximum, is also the area where the allohypse or allobar is maximum (the shaded area in Fig. 2b).

At 1500 BT 1 June, a distinct positive allohypsic area occurred at 850 hPa over the common border of Sichuan, Hubei, Hunan and Guizhou Provinces (see the arrow in Fig. 5a), and the maximum allohypsic area with a center of more than 30 gpm/3 h lay in the north of Hunan Province. Figure 5b gives 3 h allohypses of 850 hPa at 2100 BT, and there exists an SW-NE high value area (more than 20 gpm/3 h) in the Guizhou-northwest Hunan-west Hubei Provinces. Similar changes also occurred at other levels (figures omitted). Synthetically viewed from 3 h allohypses and geopotential height gradient, at the west-stretching point of subtropical high and in its adjacent areas there is a stretch of larger allohypse and geopotential height gradient areas and their horizontal scales are of meso-α and meso-β scales.

In order to show the influence of the northward jumping of subtropical high on the breaking of geostrophic balance, the distributions and changes of 850 hPa deviation winds (Fig. 6) around the westward-stretching-northward-jumping of subtropical high are calculated. It is seen from Fig. 6a that after the northward jumping, a high value area (the shaded area pointed by an arrow) of deviation wind lies in Guizhou-Hunan-Hubei along the northwest side of subtropical high. Obviously, the high value area is closely related with the breaking of geostrophic balance, which results in an SW-NE unbalanced flow field. Figure 6b reflects changes in the deviation winds around the breaking, and it can be seen from the figure that on 1 June, with the westward stretching and strengthening of subtropical high, the deviation wind also exhibits an evident strengthening trend (the area pointed by an arrow in Fig. 6b). Moreover, the area where the deviation wind is enhanced is just the place where the geostrophic balance is most violently broken. The reason that changes in geopotential height fields lead to the enhancement of geostrophic deviations in fact includes the influences of flow convergence/divergence and allobaric winds. Thus it can be seen that the sudden westward-stretching-northward-jumping of subtropical high leads to an intensive pressure increase in the area of Guizhou-Hunan-Hubei, which in turn results in the breaking of geostrophic balance, and strong geostrophic deviations. This phenomenon clearly characterizes the breaking process of geostrophic balance.

For the atmospheric motion on a rotating earth, its vorticity field contains a stationary part, which is far greater than the part of the motion relative to the earth. Here the linear equation is written as

$$\frac{\partial}{\partial t}\nabla^2\Psi = -f\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right).$$

It can be seen from the above expression that the vorticity field is always interacting with the divergence field through the Coriolis force, and the vortex is generally non-stationary. In the whole change process of motion, due to the effect of the Coriolis force, there is the interaction among vorticity, divergence and pressure fields, and the vorticity and pressure fields adjust mutually. In certain condition, when the wave energy can propagate towards infinity, the divergence field no longer changes, then the vorticity and pressure fields are in a mutual balance state. This is the physical reason for the geostrophic adjustment process of atmospheric motion, and virtually it is through divergence field that the adjustment of pressure gradient, Coriolis and inertial forces is realized, thus a balance relation on a new basis is at last achieved (Ye et al. 1988).

The above analysis clearly shows that according to the principle of geostrophic adjustment, when the West Pacific subtropical high suddenly jumps northwards and stretches westwards, and its ridge-line stretches to the south of the Changjiang River Valley, the original geostrophic balance of atmospheric motion collapses, thus triggering inertial gravity waves. The energy of unbalanced flow rapidly dissipates to an infinite space through the dispersion of inertial gravity waves, thus resulting in the rapidly adjustment of large-scale flow field. Obviously, this adjustment is a quick process. Thus it can be seen that according to the geostrophic adjustment theory, the genesis of inertial gravity waves is inevitable when the geostrophic balance is broken. It is through the dispersion of inertial gravity waves that makes the balance state be resumed.

V. GENESIS OF INERTIAL GRAVITY WAVES AND ITS FORCING TO THE STRENGTHENING OF LOW LEVEL JETS

As pointed above, the geostrophic deviations inevitably trigger inertial gravity waves,

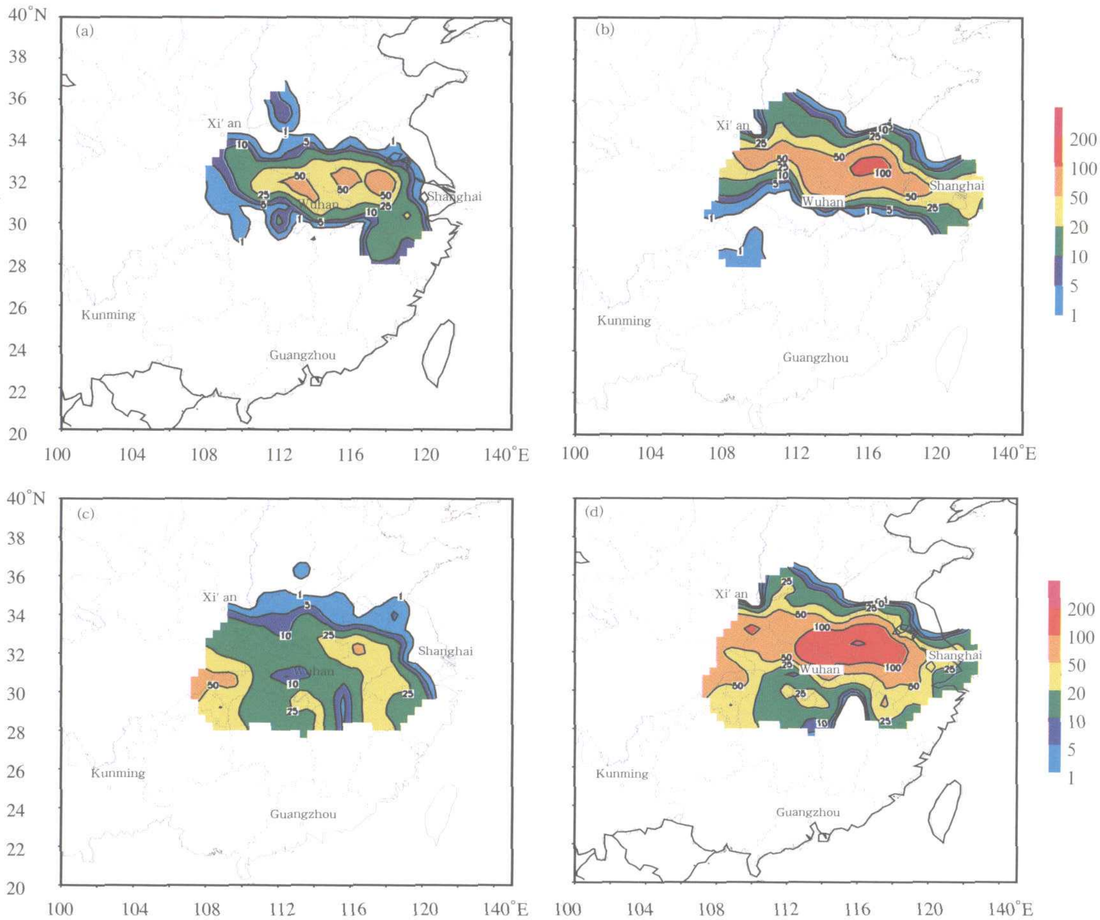

Fig.1. Daily (0800–0800 BT, a, b, c,) and total (d) rainfall (mm) in 1–3 June 2000.

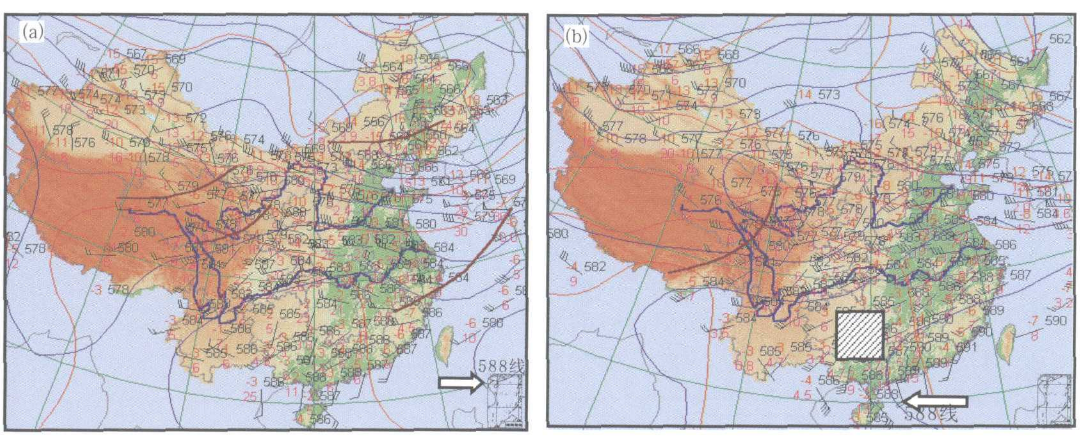

Fig.2. 500 hPa height fields (dagpm) at 2000 UTC 31 May 2000 (a) and 2000 UTC 1 June 2000 (b).

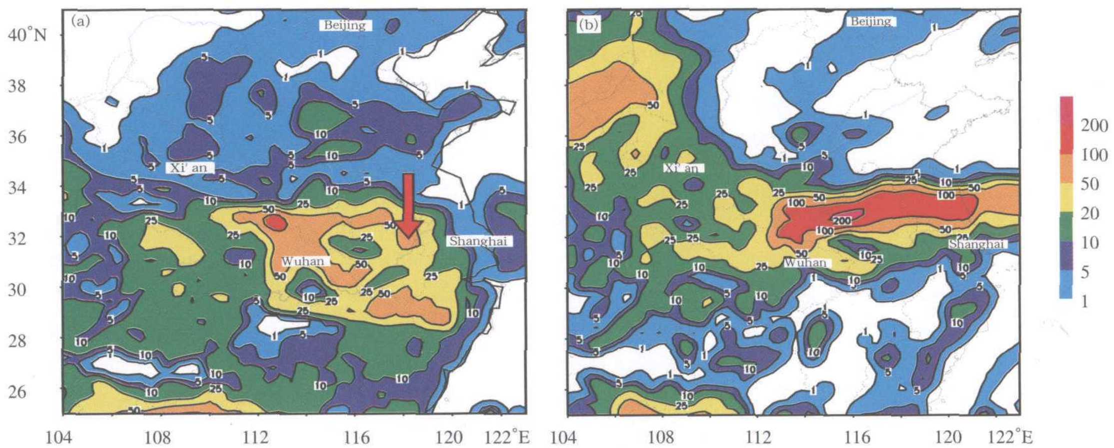

Fig.3. Simulated rainfall (mm) distributions for 0800 BT 1–0800 BT 2 June (a) and 0800 BT 2–0800 BT 3 June (b).

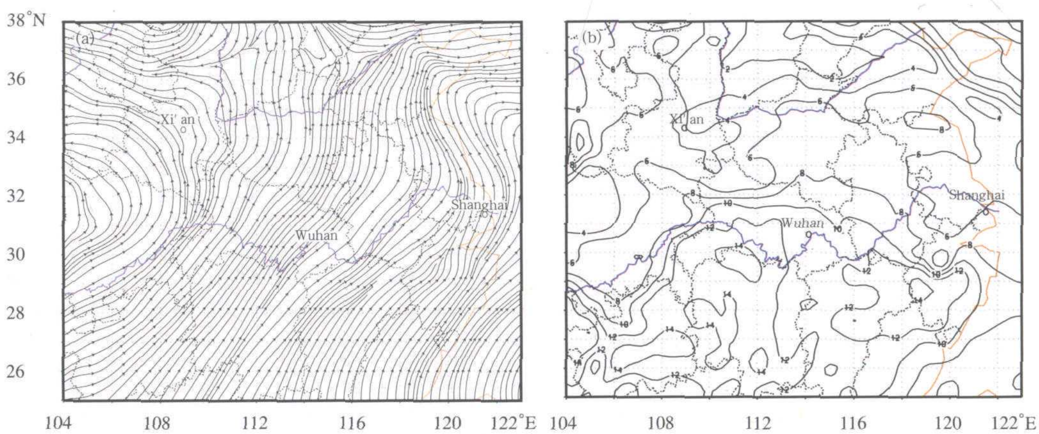

Fig.4. 700 hPa streamline (a) and isotach (b; m/s) fields at 1000 UTC 1 June.

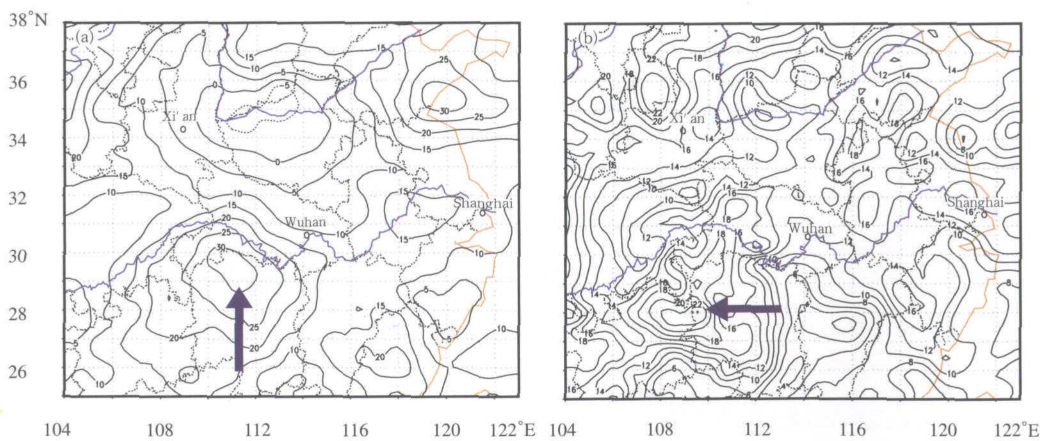

Fig.5. 850 hPa 3 h allohypsic fields at 0700 UTC (a) and 1300 UTC (b) 1 June 2000.

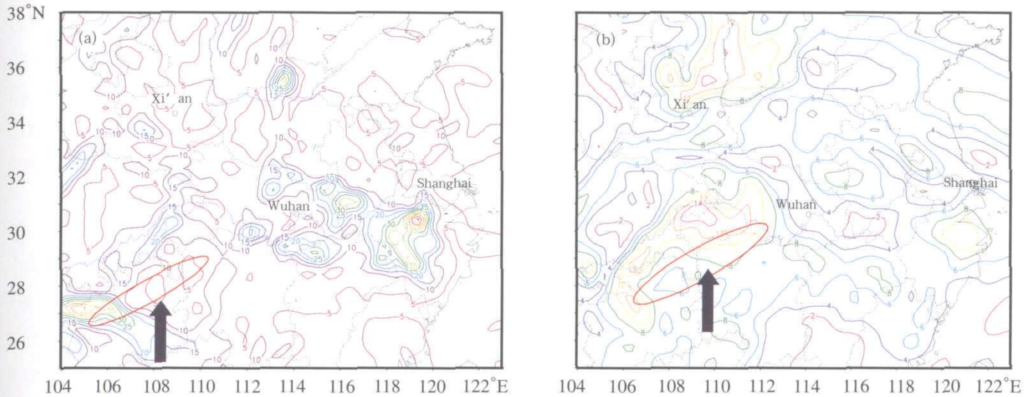

Fig.6 850 hPa deviation winds at 1300 UTC 1 June 2000 (a) and its increments in the past 12 h (b).

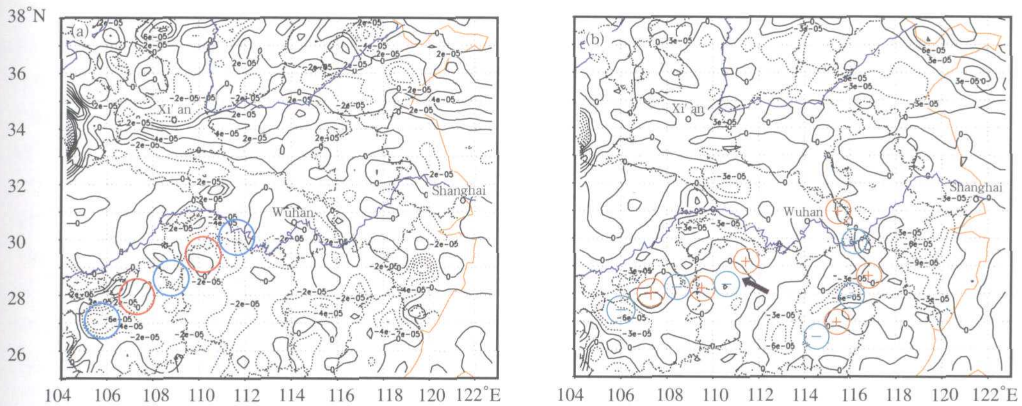

Fig.7 700 hPa divergence at 0700 UTC (a) and 1030 UTC (b) 1 June 2000.

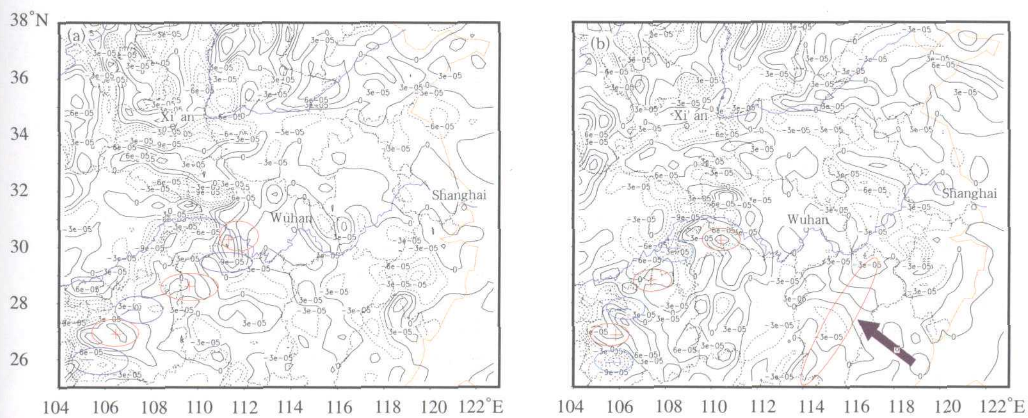

Fig.8. Divergence of 850 hPa geostrophic deviation winds at 0700 UTC (a) and 1030 UTC (b) 1 June 2000.

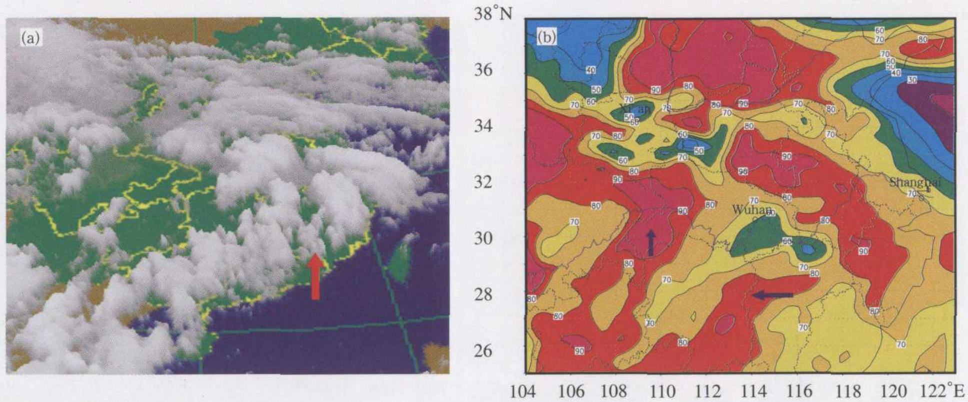

Fig.10. Infrared cloud image (a) and 850 hPa relative humidity (b) at 1000 UTC 1 June 2000.

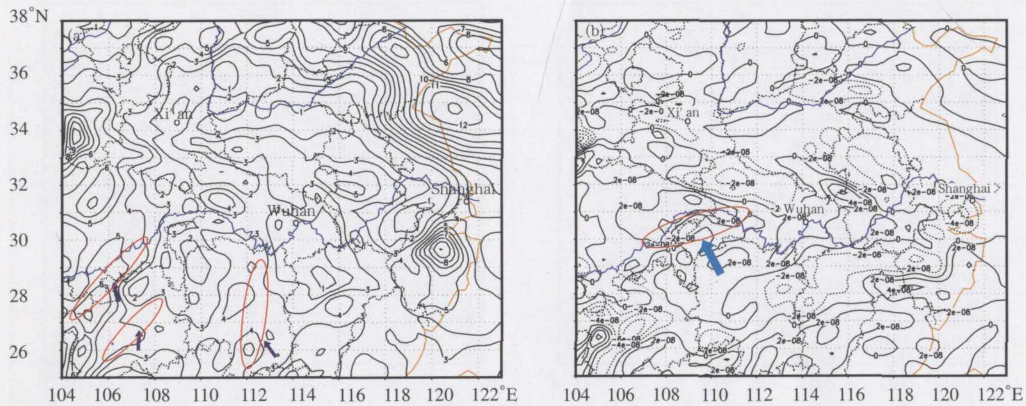

Fig.11. Differences of 700 hPa winds between 1000 and 0100 UTC (a), and 700 hPa water vapor fluxes between 1200 and 0100 UTC (b) 1 June 2000.

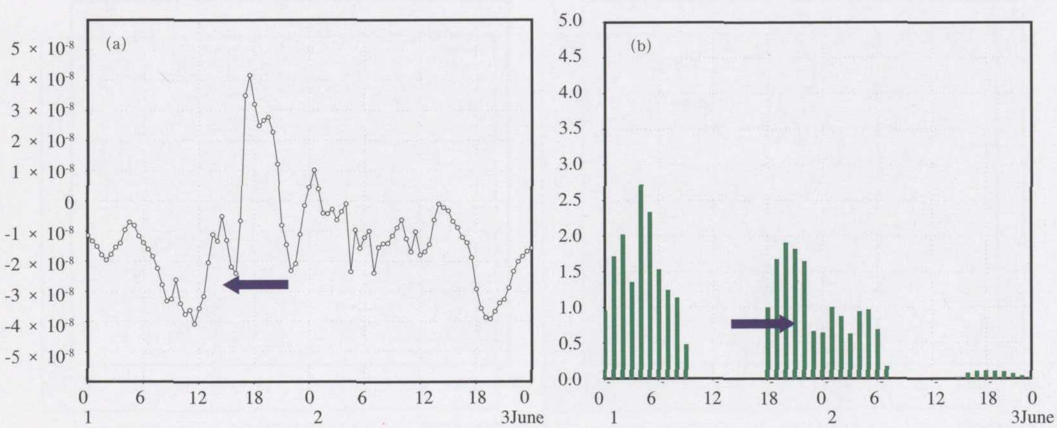

Fig.12. Temporal variations of 700 hPa water vapor flux divergence (a) and rainfall (b) at 32°N, 113°E, during 0800 BT 1–3 June 2000.

while ageostrophic disturbances disperse the unbalanced energy between pressure and wind fields to the whole space, thus achieving a new balance. Therefore, the existence and propagation of inertial gravity waves play an important role in the geostrophic adjustment. How can we determine their existence and propagation? In the light of the dynamic characteristics of inertial gravity waves, we may determine and verify their existence and propagation by using the temporal and spatial variations of divergence.

Figure 7 exhibits the spatial distribution of high spatial/temporal resolution divergence at 700 hPa output from the MM5 mesoscale numerical model.

It can be seen in Fig. 7 that there is a zonal area of divergence/convergence alternation from the northwest of Guizhou to the north of Hunan at 1500 BT 1 June. The horizontal scale of the divergence/convergence is about 150 km, and the time duration of such a structure is 1—1. 5 h. at 1830 BT 1 June, a divergence/convergence alternation zonal area again appears from the north of Guizhou to the north of Hunan, and meanwhile, such a zonal area also exists in the area from the south of Jiangxi to the common boundary of Hubei, Jiangxi and Anhui. Compared with the former alternation, the structure of divergence/convergence alternation is clearer, and its duration is about 1. 5 h. Such a distribution of divergence/convergence alternation should be virtually caused by systematical geostrophic deviation winds, and the propagation of the inertial gravity waves triggered by deviation winds may be clearly delineated by the divergence fields of the deviation winds (Fig. 8). Figure 8 displays the spatial patterns of the divergence of gerstrophic deviation winds at 850 hPa (counterparts of Fig. 7), wherein a geostrophic wind divergence/convergence alternation area is clearly seen, and it is in agreement with that at 700 hPa.

The above results clearly show the existence and propagation of the inertial gravity waves excited by geostrophic deviation winds. Similarly, their existence and propagation can also be proved by the temporal variations of the divergence of single station.

Figure 9 exhibits the temporal evolution of the 700 hPa divergence at 28°N, 111°E (pointed by an arrow in Fig. 7b) from 0800 BT 1 to 0800 BT 3 June 2000. Observed from the figure are the temporally continuous variations of divergence/convergence at the point, and values fluctuate around the base line of zero, which is just the variation feature of divergence/convergence.

The above analyses fairly show that in the process of the westward-stretching-

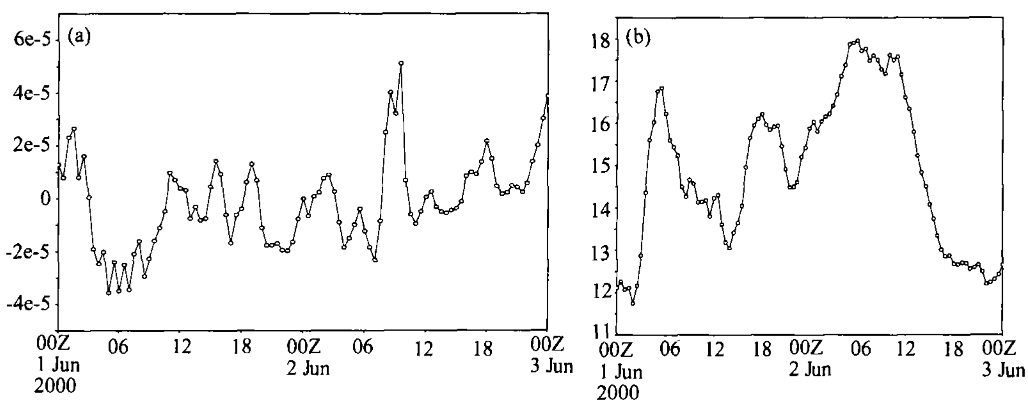

Fig. 9. 700 hPa wind speed variations at 28°N, 111°E (a), and 28°N, 109°E (b) in the period of 0800BT 1 to 0800 BT 3 June 2000.

northward-jumping of subtropical high, the inertial gravity waves, which propagate northeastwards along the northwest side of subtropical high, are triggered in the place where the geostrophic deviation is the strongest and the allobar the largest. The duration of inertial gravity waves is about 1. 5 h, which is approximately equal to the theoretical time scale of geostrophic adjustment in the middle latitude.

It should be pointed out that the other favorable condition for the enhancement and propagation of inertial gravity waves is water vapor. Because there is sufficient water vapor in the northwest side of subtropical high, under the effect of divergence/convergence, water vapor is lifted and condensed, then the released latent heat further strengthens the change of divergence. It can be seen from Fig. 10a that the convective clouds exist on the propagating path of inertial gravity waves along the northwest fringe of subtropical high, and the path accords with that in Fig. 7.

At 500 hPa, there is a zonal area of relatively larger specific humidity at 1000 UTC 1 June from Hunan to the north of Jiangxi, and Guizhou to the west of Hubei respectively (Fig. 10b), and their orientation is in general agreement with the propagating direction of inertial gravity waves. This is also reflected in Fig. 10a. This shows that the wavelike convective cloud system along the northwest fringe of subtropical high is associated with the existence of inertial gravity waves.

The analyses of divergence fields at various levels suggest that there exists a wavetrain of divergence/convergence alteration both in the boundaries between Hunan and Jiangxi, and Hunan and Guizhou, where the 3 h allohypse and the gradient of potential height are larger. The wavetrain excited from the boundary between Hunan and Jiangxi is very clear, this may be related with the topographic effect of the Luoxiao Mountains. The structure of the wavetrain at levels 850 and 900 hPa is clearer than that at 700 hPa.

After the adjustment of wind/pressure fields, the jet flow over the area of Hunan-Guizhou west and northwest of the subtropical high is evidently enhanced, this is reflected in the distributive diagram of the 700 hPa wind differences of 1000 and 0100 UTC 1 June (Fig. 11a). After about 10 h evolution, the wind speed in the jet flow area is distinctly enhanced. This further indicates that the jet flow reflected in Fig. 4 is developed in the process of inertial gravity wave dispersion.

Figure 9b displays the temporal variation of the wind speed at 28°N, 109°E from 0800 BT 1 to 0800 BT 3 June. Along the boundary of Guizhou and Hunan in Fig. 4b lies a distinctive SW-NE jet flow with several cores of more than 14 m/s. Figure 9b shows the temporal evolution of the intensity of the jet at a point within the core area, and it can be seen from the figure that the strong wind center of more than 15 m/s passes through the point three times in 48 hours. Especially, at 0600 BT 2 June, the gravity wave is the strongest, and the increment in the wind speed of the jet is also the largest, thus reflecting the effect of the northward dispersion of gravity waves on the change in the intensity of jet core. This change at last may produce a favorable influence for precipitation, i. e. the northward movement of jet cores may result in the transfer and concentration of water vapor, and then in suitable dynamic and thermodynamic conditions, the torrential rain occurs.

The above results suggest, it is the dispersion of inertial gravity waves that spreads the perturbation energy within the meso-β and meso-γ scale areas generated by the westward stretching of subtropical high, over a wider space, thus resulting in a new balance state between flow and pressure fields. Meanwhile it is the propagation of inertial gravity waves that triggers new adjustment of downstream flow and pressure fields, thus leading to the downstream extension of the jet and at last the further strengthening of the southwest LLJ. Viewed from the real propagating direction of inertial gravity waves, it is in a general agreement with the steering flow in the middle-upper troposphere, and also associated with the distribution of water vapor in the lower-middle troposphere.

The analyses of changes in regional divergence/convergence fields and the temporal variation of single station wind and divergence may fundamentally describe the genesis, propagation and influence of inertial gravity waves, and the numerical simulated results can help to give higher spatial-temporal density analyses, thus offsetting the limitation of observations.

VI. INFLUENCE OF INERTIAL GRAVITY WAVES EXCITED BY AGEOSTROPHIC FLOW ON MEIYU FRONT TORRENTIAL RAIN

Discussion in the last section has clearly shown that due to the effect of inertial gravity waves, the southwest LLJ along the west and northwest sides of the subtropical high is enhanced, which inevitably leads to the strengthening of the northward transfer of warm/moist air, thus resulting in the enhancing in the convergence of water vapor fluxes and in torrential rain along the Meiyu front.

Figure 11b exhibits the difference distribution of the 700 hPa water vapor flux divergence between 1200 UTC and 0100 UTC 1 June, i.e. the change in water vapor flux divergence around the westward stretching of the subtropical high. A distinctive change (convergence) in the divergence of water vapor flux appears in the area pointed by an arrow in Fig. 11b, indicating that due to the strengthening of jet the transfer and concentration of water vapor are both favorable to precipitation. It is just the area of water vapor concentration where a torrential rain occurs after 6 hours.

Figure 12a displays the continuously temporal variation of water vapor flux divergence at the central point of precipitation (shown with an arrow in Fig. 1a), and a continuous water vapor convergence stays at the point from the daytime to the nighttime on 1 June. During the period the amount of water vapor at the point rapidly increases (figure omitted), and a distinct precipitation starts at 0200 BT 2 June (Fig. 12b).

The above results indicate that in the condition of a satuated atmosphere the occurrence of (ageostrophic flow) balance may lead to the local anomaly of mesoscale circulation, and the inertial gravity waves are excited in unbalanced flow areas, leading to the dispersion of energy and the increase in the vertical and horizontal shears of wind fields, which will in turn cause the shear and asymmetric instabilities of the atmosphere, and is thus favorable to the genesis of new disturbances.

VII. CONCLUSIONS

To sum up, the rapid strengthening of the subtropical high breaks the geostrophic balance, leading to the rapid increase in the regional pressure gradient and then the increase in the Coriolis force (fv). The occurrence of unbalanced flow fields triggers inertial gravity waves, and through the divergence/convergence of deviation winds the unbalance energy is dispersed outwards. The theoretical analyses and numerically simulated results suggest that gravity waves mainly propagate northwards along the southwest steering flow.

The interaction of disturbances and latent heat release also influences the strengthening and propagation of gravity waves. The convergence of the perturbation flow fields triggered by gravity waves reinforces the southwest LLJ and the convergence of water vapor fluxes, thus resulting in the enhancement of convection, the release of latent heat, and the reduction in the air density ρ within mesoscale (local) areas, which in turn causes the low level convergence and the strengthening of gravity waves. Meanwhile, according to the principle of geostrophic balance, when the density reduces and f does not change, then u will increase, thus favorable to the strengthening of wind especially in the areas where water vapor is plentiful. At last the southwest LLJ is evidently strengthened. The convergence and shear of wind speed may occur in the jet belt and its vicinity, inducing larger disturbances, and playing an important role in the transport and concentration of water vapor. Especially in the left front of the jet, meso-β or meso-γ convective systems frequently occur, which facilitate the genesis and enhancement of torrential rain. Thus it can be seen that due to the sudden westward-stretching-nothward-jumping of subtropical high, the geostrophic balance is destroyed, and then the ageostrophic flow excites inertial gravity waves, leading to the enhancement of southwest LLJ and water vapor flux convergence, and thus to the strengthening of Meiyu front torrential rain. This is just one of the mechanisms for the enhancement of Meiyu front torrential rain induced by the sudden westward-stretching-northward-jumping of subtropical high. This paper focuses attention on analyzing the effects of the genesis and propagation of inertial gravity waves on Meiyu front torrential rain, however considering the complexity of torrential rain genesis, it is frequently a result of the joint effect of many factors, such as the interaction of upper and lower level jets, the transfer and convergence of water vapor, the release of unstable energy and the formation of vertical circulations, etc. Therefore, more comprehensive and systematic analyses of mechanism for torrential rain remain to be done in future.

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