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THE STUDY OF STORM RAINFALL CAUSED BY INTERACTION BETWEEN THE NON-ZONAL HIGH LEVEL JET STREAK AND TYPHOON IN THE DISTANCE

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ABSTRACT: In this paper, statistics were analyzed concerning correlation between the storm rainfall far from typhoon and non-zonal upper-level jet stream. The results show that the jet stream at 200 hPa is constantly SW (90.2 %) during the period in which storm rainfall occurs. Rainfall area lies in the right rear regions of the jet axes. While the storm intensifies, the jet tends to be stronger and turn non-zonal. With the MM4 model, numerical simulation and diagnosis were carried out for Typhoon No.9711 (Winnie) on August 19 to 20, 1997. The distant storm rainfall is tightly correlative to the jet and low-level typhoon trough. The divergence field of jet is related to the *v* component. The upper level can cause the allobaric wind convergence at low level. This is the result of the form of low-level typhoon trough and the strength of the storm. By scale analysis, it is found that there is a branch of middle scale transverse inverse circulation in the right entrance regions behind the jet below the 300-hPa level, which is very important to the maintenance and strengthening of storm rainfall. This branch of inverse circulation is relative to the reinforcement of jet's non-zonal characteristics. From the field of mesoscale divergence field and non-zonal wind field, we know that the stronger symmetry caused by transverse circulation in the two sides of the jet, rainfall' s feedback and reinforcement of jet' s non-zonal characteristics had lead to positive feedback mechanism that was favorable of storm rainfall' s strengthening.

Key words: non-zonal upper level jet stream; storm rainfall far from typhoon; dynamic pressure-decreasing zone

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1 INTRODUCTION

The upper-level jet is an intense wind zone that is greater than 30 m/s at 300 ~ 200 hPa. As the westerly circulation is a dominant phenomenon in the middle latitudes, basic air-flows are generalized to zonal westerly winds in most of the theoretic studies on high-level jet streams, examples of which refer to Uccellini[1] et al. The zonal westerly winds are an important characteristic of the real atmosphere, but basic flows are usually non-zonal in the strict sense and latitudinal flows (as in periods of low-index circulation) can be quite strong. By the pattern of axis, Huang et al[2]. grouped high-level jets into cyclonic bending before troughs (65%), cyclonic bending after troughs (26%) and straight flows (9%). It is an indication that high-level jet widely shows non-zonal characteristics.

With varying rain rates, Ding[3] et al. made diagnostic comparisons and numerical experiments,

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discovering that upper-level jets responsible for heavy precipitation in the north during two cases of typhoon were both NE-SW directed while most of the precipitation would be confined to areas south of 25°N and remain weak even with strong typhoons, if straight westerly jets are prevailing at upper levels. By comprehensive survey of typhoons (which are documented in *Yearly Books for Typhoons*) from 1965 to 1992 for heavy storm-induced precipitation during northward shift, they point out that typhoons with such features are generally in the right rear portion of a SW high-level jet. In her study of heavy rain that is subject to typhoon landfall, Luo[4] also suggested the presence of obvious NE-SW jets at the upper level of 200 hPa. Li[5] was successful during a composite study in identifying consistent southwesterly wind at 300 hPa over the storm rain, which was caused by an inverse typhoon trough.

To sum up what has been discussed, the latitudinal southerly component is playing a vital role in causing and maintaining heavy rain induced by the typhoon. We should therefore focus the effort on studying heavy rain far away from typhoons from the point of non-zonal upper-level jet streams.

2 DATA, METHODS AND INTRODUCTION TO THE MODEL

The *Yearly Books for Typhoons* and historical weather maps compiled by the Central Observatory are used to conduct a statistic study of correlation between non-zonal high-level jets and far-away typhoon-induced hard rain. Among the heavy rain caused by historical intense typhoons surveyed indiscriminately, the regions where there are distant heavy rains include Beijing, Tianjin, Hebei, Shandong and Henan. For jet streams, 200-hPa data at 2000 L.T. on the day of incidence are selected (500-hPa data are used instead for years 1956 ~ 1996 due to relevant data shortage); for daily rainfall, data obtained at 0800 L.T. of the following day are used. Data through comprehensive check amount to 51 cases for the period from 1956 to 1996. Only 5 of them are with heavy rain without obvious signs of SW upper-level jets, taking up 9.8%. Jiang[6] named heavy rain precipitating over 1000 km one with long-distance storm rain. As the diameter of typhoons is mostly in the range of 600 ~ 1000 km[7], heavy rain taking place 500 ~ 1000 km from the typhoon is called a distant storm rain in this work. Detailed statistic analysis is also conducted for such rain over the period from 1980 to 1997.

The model used in the work is a MM4 (PSU/NCAR), which is a mesoscale numerical prediction model for limited area that is stratified into 15 vertical layers in the σ coordinates[8]. The model is already widely used in numerical experiments for mesoscale heavy rain. The diagnostic data in the work is the raw information at upper and surface levels on August 19 ~ 20, 1997. The upper-level data is 2 times daily (0000 and 1200 GMT) and surface data is 4 times daily (0000, 0600, 1200 and 1800 GMT).

Large-scale condensation, factors like feedback from latent heat due to cumulus convective condensation and longwave and shortwave radiation, are considered. Specifically, the Kuo-Anthes Scheme is adopted in parameterizing the cumulus convection and the spongy condition is used in the lateral boundary[9].

For the model initial field, the objective analysis data, which are used in diagnosis at 0000 on August 19, are included. The point (35°N, 120°E) is chosen as the center of the model. Horizontal grid intervals are 60 km and horizontal grid number is 51×51. Basic element field output by the model employs the Lagrange interpolation technique in the vertical direction, resulting in 14 layers with unequal intervals. The model undergoes a 24-h integration at steps of 90 s and produces predictions every 3 hours.

3 FEATURES OF STATISTICS IN CORRELATION BETWEEN NON-ZONAL UPPER-LEVEL JETS AND DISTANT STORM RAIN

As shown in Tab.1, July, August and September are the months when heavy storm-induced rains are caused. August is the most frequent month by the time of landfall, amounting to 8 typhoons in all, followed by September, 5, and July, 2. The areas of landfall include the provinces of Taiwan, Fujian, Guangdong and Zhejiang, in which storms landing on Taiwan usually make another 2 or 3 landfalls in Fujian and sometimes a secondary center is formed. The route of landfall is generally westward before changing direction or northwestward until disappearance inland. At the time of landfall, the typhoon's pressure is between 960 hPa and 980 hPa near the center with maximum winds varying from Force 8 to Force 12 on the Beaufort scale. Precipitation usually lasts 3 ~ 5 days and 10 days for the longest duration (Typhoon No.8616).

Tab.1 The precipitation, typhoon and jet when long-distance heavy rain occurs (* rainfall over life cycle)

code	Time of heavy rain occurrence	Location of rainfall center °E	°N	rainfall mm	200-hPa jet center °E, °N	Intensity of jets ms^{-1}	WD in jets	Location of the eye °E, °N	Pressure of the eye hPa
8012	Aug. 30	120	33	157	120, 40	56	SW	117, 29	1003
8114	Sept. 2			94	110, 45	68	WSW	123, 31	960
8209	Aug. 1	114	36	160	115, 48	36	SSW	114, 32	995
8303	Jul. 19	118	35	108	113, 42	60	WSW	103, 21	990
8407	Aug. 10	117	37	193	122, 47	64	SW	115, 34	997
8411	Sept. 1	116	30	240	137, 45	84	SW	114, 25	992
8616	Sept. 6	117	28	75	118, 38	56	SW	108, 20	970
8707	Jul. 29	116	33	70	118, 37	40	WSW	120, 34	990
8807	Aug. 10	112	33	229	90, 46	48	SW	112, 32	1002
8921	Sept. 14	120	30	90	130, 45	52	WSW	120, 27	995
9012	Aug. 21	117	30	89	137, 45	56	SW	119, 25	980
9216	Sept. 1 ~ 2	117	34	246*	127, 45	60	SW	119, 26	986
9417	Aug. 24 ~ 25	120	36	195*		44	WSW		
9608	Aug. 1 ~ 4	113	36	247*			SW		
9711	Aug. 20	121	37	198	122, 44	76	SW	118, 32	996

More is discovered in the statistical study: When there is such long-distance heavy rain, the upper levels are usually dominant with the SW jet and the central intensity ranges from 40 m/s to 80 m/s at the level of 200 hPa. The rain usually centers in the right rear portion of the upper-level jet, locating 5 ~ 15 latitudes more to the south and 5 ~ 20 longitudes more to the west (In the case of Typhoon No.8807, the rain area is 10 latitudes eastward of the 200-hPa jet center). Moreover, the precipitating area is usually at the eye or north of the depression center by 2 ~ 8 latitudes. In the course of raining, the center of typhoon is normally within the range of 980 ~ 990 hPa and its maximum wind is 10 ~ 35 m/s.

Over the preceding period for a long-distance heavy rain (6 ~ 12 hours), the typhoon is usually filled and weakened while the 200-hPa jet is increasing, which includes the increase of central value and lengthening of the axis, of the jet stream. Studying daily evolution of the jet and heavy rain for Typhoons No.8012, 8407, 8411, 9012, 9216 and 9711, we know that the heavy rain does not become the strongest when the jet has the maximum intensity, and the amplitude increases by a significant margin when the 200-hPa jet having a trend of strengthening by turning upright (non-zonal).

To summarize what has been discussed above, the non-zonal upper-level jet streams have inseparable links with distant storm-induced heavy rain. In view of it, the current work will carry out diagnostic study and numerical simulation of one such process caused by Typhoon Winnie from the point of non-zonal upper-level jet, in the hope that more efforts are spent on investigating into the mechanism for heavy rain as induced by typhoons active over long distance.

4 INTRODUCTION TO BACKGROUND AND PROCESS OF THE WEATHER WITH TYPHOON WINNIE

4.1 *Large-scale circulation background and weather situation*

Making landfall on Wenling, Zhejiang province at 1330 GMT August 18, Typhoon Winnie had maximum wind over 40 m/s approaching the coast. With the northwest migration of the eye to Anhui province via northwestern Zhejiang where it weakened to a tropical storm, an inverse typhoon trough that formed in the northeast quadrant moved northward with it, eventually filling it up at 0000 GMT August 20.

By 0000 GMT August 19, isobaric contour 588 had reached the Shandong Pen. while the typhoon center traveled to areas near Changhua, Zhejiang, forming a SE-by-S jet stream with wind speed up to 36 m/s at 850 hPa over the coast of East China that stretched itself all the way from the waters off the eastern coast of Taiwan to offshore region in northern Jiangsu province. By 1200 GMT August 19, the jet extended to Shandong Pen. when SE winds increased to 22 m/s at Qingdao and Chengshantou. Over the level of 200 hPa, however, a strong SW jet had been active from southern Shanxi to Northeast China, with the central winds at 76 m/s inside the strongest wind zone and the center at Point (44°N, 122°E). Such allocation, with jets distributing on both upper and lower levels, is favorable for strong large-scale ascending motion to generate in front of the jet at low level and in the right rear part of one at upper level, which is associated with an increased subtropical high (Fig.1).

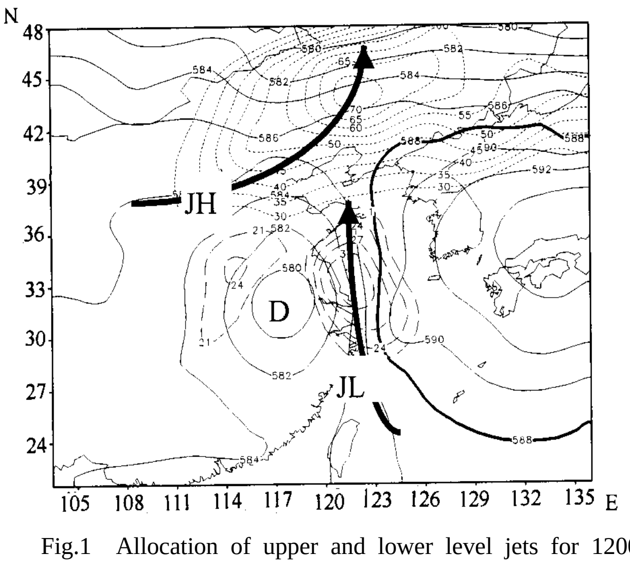

Fig.1 Allocation of upper and lower level jets for 1200 GMT 19 August 1997 (solid line: isopotential at 500 hPa; short broken line: isovel for ≥30 m/s at 200 hPa; long broken line: ≥30 m/s at 850 hPa; vectors: axis of upper and lower level jets)

4.2 *Brief introduction to precipitation observed*

From 0000 GMT August 19 to 2000 GMT August 20 (Fig.2a), the typhoon had caused unusually heavy rain in Shandong Pen. with rainfall generally around 110 mm and more than 200 mm at one or two stations. At Shidao, Shandong province, 1-h precipitation had a maximum of 78.7 mm from 1400 to 1500 GMT on August 19. Except for a few stations, the province received heavy rain almost everywhere. A total of 72 stations had rainfall over 100 mm with Jimo having the highest cycle precipitation of 482.5 mm.

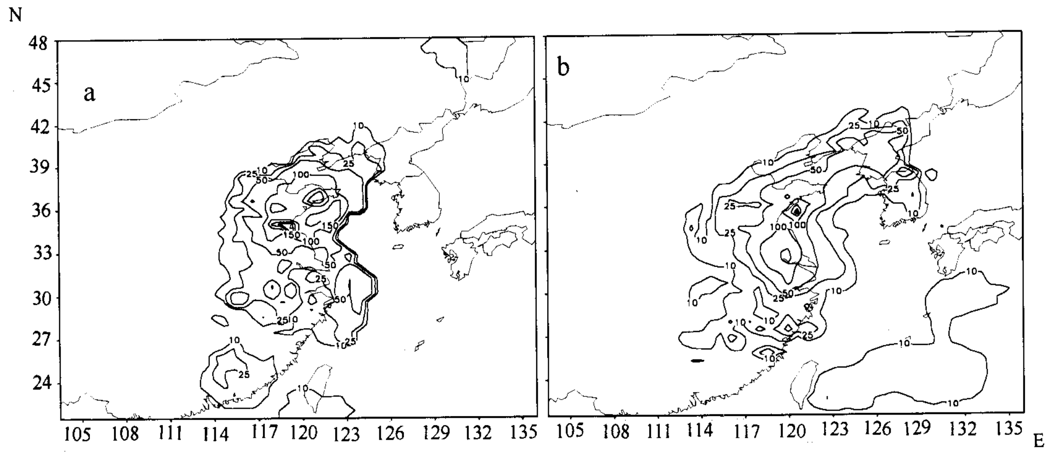

Fig.2 Observed (a) and forecast (b) rainfall for 0000 GMT August 19 ~ 0000 GMT August 20, 1997.

5 ANALYSIS OF PREDICTION RESULTS

5.1 *Comparison with observed basic fields*

From 0000 to 1200 19 August, the center of the storm moved northwest and was in Yuexi, Anhui province (31.8°N, 118°E) with the pressure near it weakening from 980 hPa at 0000 to 994 hPa while the forecast position was at 30.5°N, 117.5°E and the central pressure was 992 hPa. By 0000 August 20 (Fig.3), the eye had moved to 35°N, 118.2°E, a shift of 4 ~ 5 latitudes to the north and the pressure surrounding it dropped to 999 hPa in contrast to the position (32.5°N, 117.2°E) and the pressure value of 995 hPa in the forecast field. As indicated in the surface pressure field, the model is capable of modeling the trend of the northward shift, filling-up and weakening of the typhoon though with slower speed and higher intensity.

Studying the omnidirectional contours of wind speed for the geopotential field, 200-hPa and 850-hPa jets (figure omitted), one knows that the model gives a general model result bearing largely the same situation of circulation as the observation.

There are two areas of precipitation locating north and south of the forecast field of rainfall

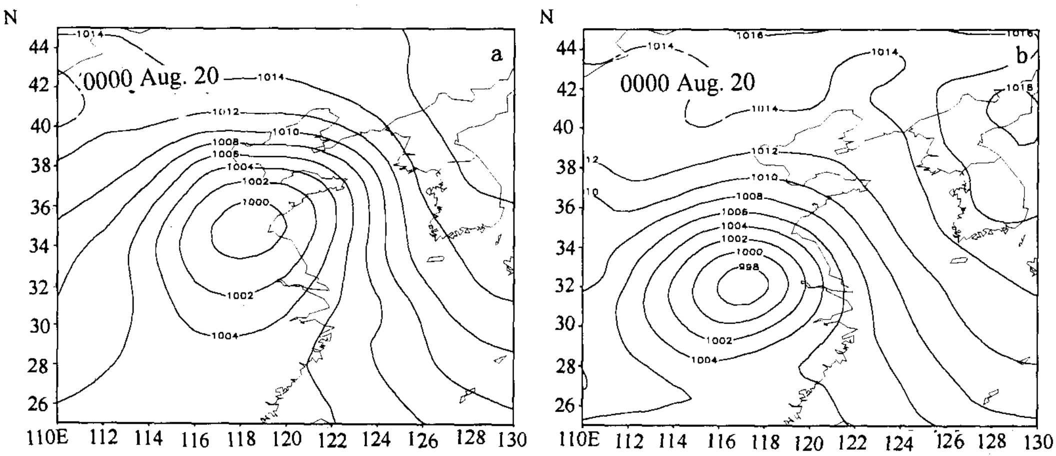

Fig.3 Observed (a) and forecast (b) sea-surface pressure for 0000 August 20, 1997.

when the integration enters the 24th hour (Fig.2b). The center of the southern area is at 32.5°N, 119°E with an extreme of 162 mm while that of the northern one at 35.5°N, 120.75°E with an extreme of 207 mm. It is clear that precipitation is stronger in the distance than in the circulation of typhoon. Large-scale trend of precipitation agrees with the field observed (Fig.2a). The latter also has two centers of rain, one in the south and the other north. The center of the southern raining area is at 34.5°N, 119°E with the extreme of 209 mm and the northern one at 37.0°N, 121°E with the extreme of 198 mm. The forecast field is about 2 latitudes more to the south than the observation. It matches with the southward trend in the system simulation. From the comparison of 6-h rainfall, we could find that the most intense phase of precipitation occurs from 06 to 24 hours for both forecast and observation (figure omitted).

In summary, the current numerical simulation has been successful in modeling the general moving direction / speed, jets at upper and lower levels, frontal zone and variation of system intensity concerning the surface and upper-level regimes, during the decay of the typhoon. It is specially noted that the location of rain area of the typhoon-related heavy rain is predicted (in north and south areas). Good agreement has been found between the simulation and observation as far as the long-distant precipitation (in the northern area) is concerned.

5.2 *Diagnosis of non-zonal effect of the jet*

In view of the fact that some kind of response exists between the increase of storm rain and the upright-turning of the 200-hPa jet, as revealed by statistical facts and diagnostic results. In the sections followed, some diagnostic attempts have been made from the viewpoint of *u* and *v* wind components.

5.2.1 DIAGNOSIS WITH *u* AND *v* COMPONENTS

Idealizing upper-level jets to zonal westerly winds, Uccellini [1] concludes that momentum propagates downward. The question is that which of the *u* and *v* components in the upper-level jets has more of the downward transfer of momentum. For this purpose, a temporal profile of *u* and *v* wind components is made through the center of the northward rain area (35.6°N, 120.7°E). As indicated by Fig.4 (a & b), the downward propagation of momentum is displayed mainly as *v* rather than *u* component, which further proves the role of jet's non-zonality. Fig.4b shows that the fiercest

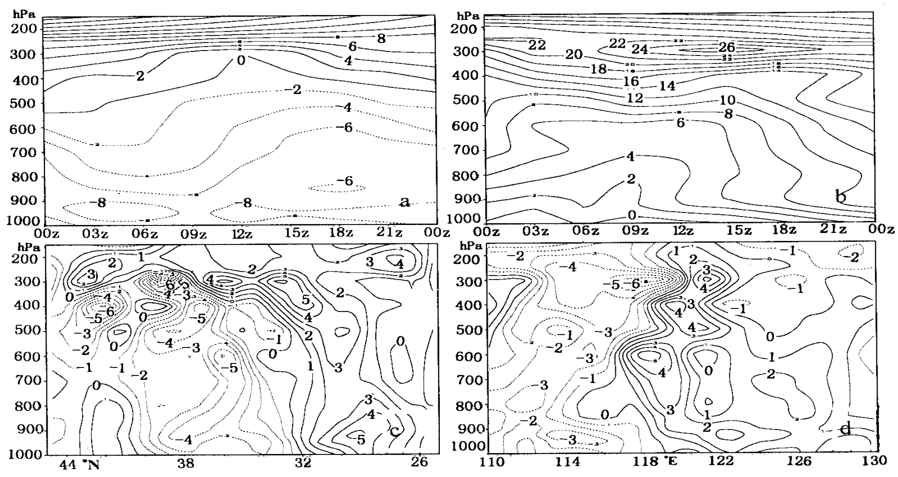

Fig.4 Twenty-four-hour evolution of *u* (a) and *v* (b) components and 21-h forecast divergence of *v* (c) and *u* (d) components.

change of the process was indeed after 1500 and an obvious turning point was even present at 2100, which coincides with the most intense phase of precipitation. The cause can be sought from the allocation of a SW jet at upper levels and a SE jet at lower levels so that the southerly component of both jets take the same direction to increase the southerly wind at lower levels. The westerly component of the upper jet goes in opposite direction with the easterly component of the lower one such that the easterly wind is curbed, resulting in more obvious downward propagation of momentum in the non-zonal wind component.

As the integration produces over 50 mm for a 3-h period from 2100 August 19 to 0000 August 20 at Point (35.6°N, 120.7°E), we choose the *u* and *v* wind components integrated for 21 hours and diversity to made diagnostic charts Fig.4 (c & d). As shown in the north-south profile of the *v*-component diversity, there is convergence of southerly wind below the level of 400 hPa but divergence above it. The divergence is the strongest at 300 hPa while a divergence-free layer is found at 500 hPa. It superposes the centers of divergence and convergence, being favorable for precipitation to occur. The precipitation maximum is just over the superposition at 35.6°N. Examining the *u* component and the east-west profile of its diversity, we can see that there is weak westerly divergence at upper levels but easterly divergence at lower levels, over the area of precipitation. Divergence is consistent throughout the entire air column and there is not any superposition of divergence/convergence centers in terms of the *v*-component divergence field. It is apparently not a favorable condition for lower-level converging, ascending motion and precipitation to occur. One possible cause may be that precipitation may take place in the right rear part of the upper-level jet and the left front part of the lower-level one, i.e. the southwestern of the upper but northwest of the lower. The downward propagation of momentum of the non-zonal southerly component in the upper-level jet has strengthened the southerly component of the lower-level jet in the southern part of the rain area and intensified the northward transportation of moisture and convergence at lower levels. In the meantime, the upper-level jet in the northern portion of rain area in intensifying the southerly component over there and divergence over the raining area. A positive feedback mechanism is thus formed that is favorable for precipitation. In contrast, the zonal westerly component of the upper-level jet transmits the momentum downward to inhibit the easterly component of the lower-level jet, checking at the same time the transfer of moisture and formation of converging field at middle and lower levels. It is then obvious that the increased divergence due to zonal westerly at upper levels is not allocated with favorable field of convergence at lower levels, being unfavorable for the formation of positive mechanism of precipitation. In a word, the facts above are additional evidence that shows how important it is for non-zonality of upper-level jets in the evolution of typhoon-induced heavy rain far away from the storm itself.

5.2.2 AGEOSTROPHIC FIELD AT 200 hPa AND STRENGTHENING OF *v* COMPONENT

In a study[10] addressing the issue of relation between large-scale gravity inertia waves in 200-hPa jet zone and heavy rain, it is pointed out that strong ageostrophic effect present in the 200-hPa jet can excite gravity inertia waves at large scale and spread it around. It is mostly likely for the energy of waves to develop at the right rear part of the upper-level jet. Figs. 5a & 5b show the 200-hPa ageostrophic wind field 21 hours into integration, of which the area of precipitation is in the right rear portion of the upper-level jet in the last 3 hours and corresponds to the ageostrophic divergence field (figure omitted). As what is presented in reference [3], the southwesterly jet ahead of an upper-level trough is favorable to the generation of a divergence field to the right rear part on one hand and an ageostrophic divergence field is also present in front of the upper-level trough itself; the two divergence fields act together to constitute a more favorable condition for ascending motion and precipitation increase. From Fig.5a, one knows that $u-u_g$ field is subgeostrophic above the rain area, being about –15 ms^{-1}. More is known from the expressions below:

$$\frac{\partial v}{\partial t} = -f(u - u_g)$$

$$\frac{\partial u}{\partial t} = f(v - v_g)$$

The strengthening of the *v* field of the 200-hPa non-zonal wind component is related with the ageostrophic wind (i.e. strong subgeostrophic wind of $u - u_g$). In other words, the adjustment of ageostrophic wind has made the jet more non-zonal. As $u_g = -\frac{g}{f}\frac{\partial z}{\partial y}$, the magnitude of u_g relates to the gradient of altitude. The large warm advection and latent heat release of the heavy-rain area has increased the gradient to result in high u_g and favors the strengthening of *v* field. In Fig.5b, the $v - v_g$ is weak subgeostrophic or super-geostrophic over the rain area, with the obvious result that the increase of *u* field is weaker than that of *v* field. It prompts us into belief that the warm advection and the release of latent heat at 200 hPa has greatly strengthened the subgeostrophic wind $u - u_g$ and increased $\frac{\partial v}{\partial t}$, making the jet much more non-zonal. It is indeed true that the strengthening and upright-turning of upper-level jets is closely related with heavy rain; southwesterly jets usually bring about strong warm advection in addition to the release of latent heat due to heavy rain so that the isobaric surface is lifted, $\frac{\partial z}{\partial y}$ and u_g increased, thus favoring the strengthening of *v* field.

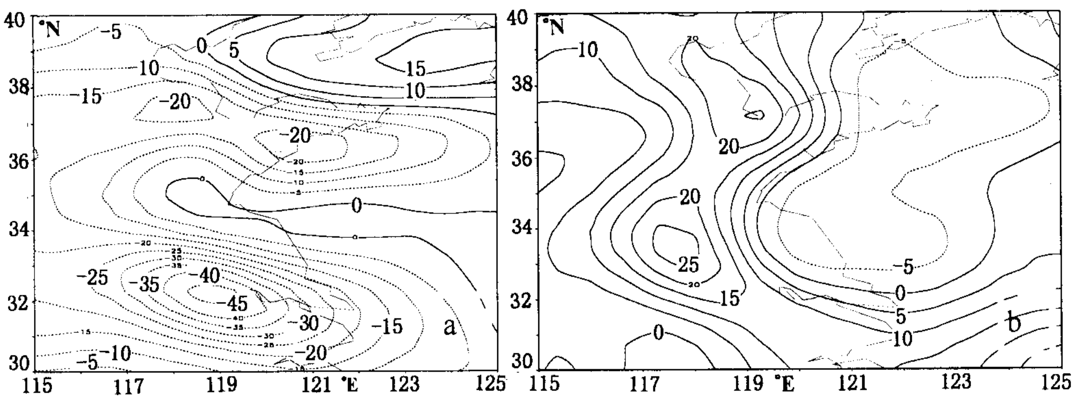

Fig.5 21-h forecast $u - u_g$ (a) and $v - v_g$ (b) at 200 hPa.

5.3 *Non-zonal wind during heavy rain and mesoscale systems*

In China, summertime heavy rain is usually caused by mesoscale or subsynoptic scale regimes with horizontal scale at 200 ~ 500 km that are superposed on a large-scale field. The relationship between the activity of mesoscale systems and non-zonal winds is an issue to discuss in future. Next is our study of the mesoscale field of disturbance that is split up using 25-poiont filter smoothing operator[11].

On meso- and fine-scale fields at 850 hPa that have been filtered, there are always northerly and southerly flows joining over the region near the Shandong Peninsula, which is corresponding to the area of precipitation (figure omitted).

Figs.6a & 6b give the vertical profile of vertical circulation in the longitude (v - w) that has been filtered and cuts across the center of the northern rain area (35.5°N, 120.6°E) at different time levels of integration. According to the theory of Uccellini[1], a secondary circulation forms as convergence appears on the left and divergence on the right of the inlet of the upper-level jet, the air motion descending on the left and ascending on the right. For the increasing phase of the long-distance heavy rain (12 hours into the integration), the circulation on the large scale (figure omitted) is in an ideal state with descending motion on the left and ascending motion on the right. On the mesoscale (Fig.6), there is one more circulation, which is small, to the right of the jet at 300 hPa, with the descending branch at 40°N and the ascending one south of 37°N. Connected with the strong ascending airflow over the rain area (near 35.5°N), the branch forms in association with the convergence / divergence of the v speed field at 300 hPa. It is clear from Figs.6c & 6d that a high-value center appears over the Shandong Peninsula (the right rear part of the jet) at 300 hPa, the center of which increases with time and air sinks in convergence on the north side but rises in divergence on the south side. The mesoscale circulation is thus generated.

It is apparent that the sinking branch of the secondary circulation that forms in the convergence field to the left of the upper-level jet helps increase the northerly component at lower levels; the downward transportation of the southerly component increases the southerly component at

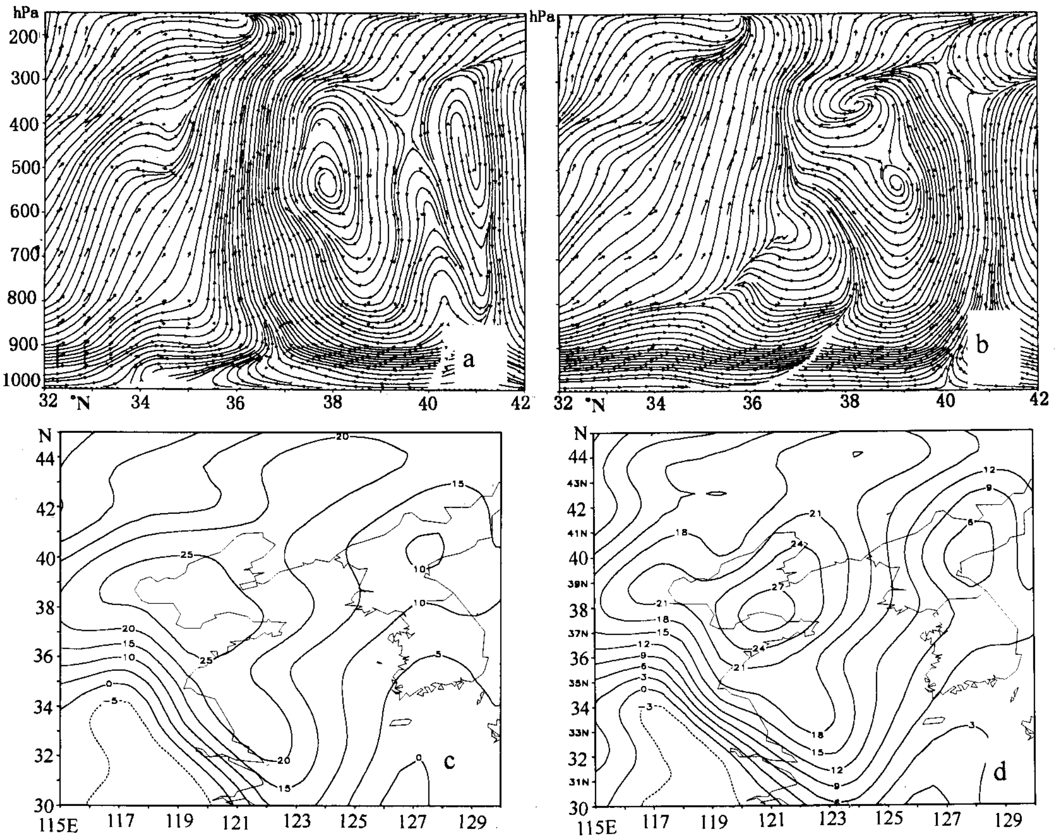

Fig.6 12-h forecast v-w filtered circulation (a) and v component (c), 18-h forecast v-w filtered circulation (b) and v component (d).

lower levels so that moisture momentum and warm advection are transported to the area of precipitation more vigorously. As a result, air motion rises to the right of the jet and feedback due to latent heat from precipitation further strengthens the rising motion and increases the non-zonal wind field (*v* field) at upper levels. The increased *v* field in turn gives rise to mesoscale circulation and enhances it, resulting in the increase of ascending motion over the area of heavy rain. It is in such manner that a positive feedback mechanism comes to being that favors the increase of heavy rain responding in the distance.

5.4 *Formation of upper-level jet and lower-level inverted trough*

From 0000 19 August to 0000 20 August, an inverted trough of typhoon developed and extended to Shandong province. Especially, the trough extended northward for 3 latitudes and the low-level jet expanded to the Shandong Peninsula, over the last 12 hours. Reference [12] holds that the formation of inverted troughs are related with dynamic decrease of pressure in the right rear portion of the upper-level jet. To confirm such relationship, we have decomposed the surface pressure variation into components contributed by the movement of systems (such as typhoons) and dynamic effects. As the system of interest involves with the most intense pressure system, variation of pressure is believed to come mostly from the typhoon movement. By setting up moving coordinates with the typhoon center as the origin, we subtracted gridpoint values around the eye from those for an earlier time to obtain dynamic pressure variation. It removes systematic variation of pressure caused by the typhoon's movement. The mesh grids are 31×31 at intervals of 60 km with (16, 16) the coordinates of the typhoon. The forecasts well describe how the typhoon fills up and weakens. Fig.7 gives 3-h pressure variation at time levels 12 and 18 hours in the integration. It is now known that there is a dynamic pressure decrease at the third quadrant of the circle setting the typhoon center as the origin when the pressure keeps rising near the center. Rather than in front of it, such dynamic pressure decreasing happens far north in the distance. Furthermore, the maximum center of negative pressure variation is roughly in agreement with the divergence on the right of the 200-hPa jet at the upper level. It is obvious that the negative variation of pressure is related to the jet at the 200-hPa level. Fig.7 shows that the center of the negative pressure variation is as strong as –1.5 hPa at 1200 and located southward, with the northern section generally positive variation, which may be the result of frontal activity. At 1800, however, a large stretch of negative variation appears in this section with the center as strong as –1 hPa that is consistent with the upper-level jet in both location and direction. Correspondingly, precipitation increases after 1800. From Figs.7c & 7d, we know that at this time the inverted trough is also much extended to the north. It is corresponding to some degree that the section of the inverted trough is indeed related with the upper-level jet at 200 hPa. A 3-h wind variation wind field is know by subtracting integration for the previous 3 hours from wind field at a particular time level during the model integration. Examining the 3-h wind variation field at 850 hPa, we know that the wind variation field for the rain area is divergent at 0600 but becomes convergent at 1200 and beyond. The convergence field is the region where the southwesterly and southeasterly meet in shear near 34°N in the southern part of Shandong Peninsula (figure omitted). It is seen that the formation of the shear wind field, which is the main cause for the generation of inverted typhoon trough, is corresponding to the intensity of dynamic pressure decrease. It is now obvious that the dynamic decrease of pressure caused by the 200-hPa upper-level jet is closely related with the formation of the inverted typhoon trough, which in turn plays a vital role in the increase of heavy rain in the distance.

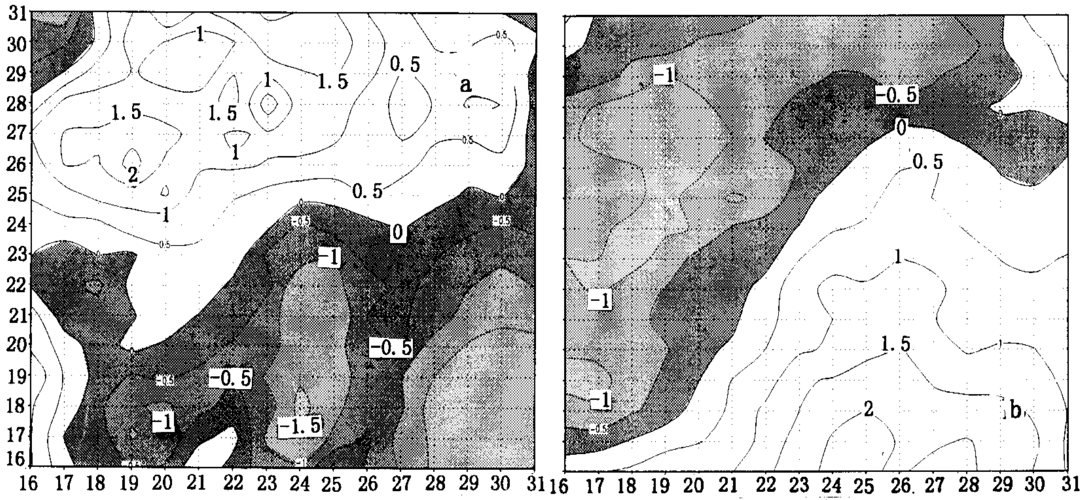

Fig.7 3-h dynamic pressure decreases 12 hours (a) and 18 hours (b) into the integration.

6 CONCLUDING REMARKS

a. A statistic study of the correlation between non-zonal upper-level jets and typhoon-related heavy rain in the distance shows that the latter occurs in close association with the former. When the heavy rain occurs, the southwesterly jet usually prevails at the level of 200 hPa and the area of precipitation is in the right rear portion of an upper-level jet. When the rain intensifies, the jet usually tends to increase and turn upright, i.e. becoming more non-zonal. It shows that the non-zonality of the upper-level jet is playing an essential role in heavy precipitation in the distance. The finding has important implication for the forecast of heavy rain induced by typhoons.

b. The intensification of the typhoon-induced heavy rain in the distance is obviously related with the formation of an inverted typhoon trough and non-zonal upper-level jets. As shown in a diagnostic study of 3-h variation, the dynamic decrease of pressure occurs below the upper-level jet far away from the typhoon rather than before it. It is caused by upper-level divergence that is resulted from non-zonal jet at the level. The pressure decrease zone is consistent with the formation and strengthening / northward extension of the inverted zone in either time period or location. The 3-h wind variation field at 850 hPa changes in phase with the dynamic pressure decreases, with the latter producing a cyclonic shear in the former. When the pressure decrease is strong, the cyclonic wind shear is strengthened, contributing to the formation of the inverted typhoon trough. It is true otherwise. The increased cyclonic wind shear in the wind variation field resulting from the pressure drop is the main cause for the formation of the inverted trough.

c. The divergence of non-zonal wind decreases the pressure at lower levels to form a cyclonic wind variation field, leading to the formation and strengthening of the inverted trough as well as the increase of precipitation. The downward transfer increases the southerly component at lower levels and helps transport the momentum of moisture over the rain area. The increased non-zonal wind is associated with a strong ageostrophic field $u-u_g$ in the right rear portion of the jet. The increase of v field brings forth a mesoscale longitudinal circulation cell on the right rear side of the jet. As the southern branch of the cell ascends and joins the rising branch in the area of heavy rain, a positive feedback forms and precipitation increases in an environment in which the southerly component further intensifies because of an increased northerly flow due to the release of latent heat over the rain area.

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