The Use of Dual–Doppler Radar Data in the Study of 1998 Meiyu Frontal Precipitation in Huaihe River Basin①

Xu Hui (徐 晖), Zhang Weiping (张卫平), Lang Xuxing (郎需兴)

Guo Xia (郭 霞), Ge Wenzhong (葛文忠), Dang Renqing (党人庆)

Department of Atmospheric Sciences, Nanjing University, Nanjing 210093

Takao Takeda (武田乔男)

Institute for Hydrospheric–Atmospheric Sciences, Nagoya University, Japan

(Received June 17, 1999; revised January 21, 2000)

ABSTRACT

During the Meiyu period in June and July of 1998, intensified field observations have been carried out for the project "Huaihe River Basin Energy and Water Cycle Experiment (HUBEX)". For studying Meiyu front and its precipitation in Huaihe River basin, the present paper has performed analysis on the middle and lower level wind fields in the troposphere by using the radar data obtained from the two Doppler radars located at Fengtai district and Shouxian County.

From June 29 to July 3 in 1998, the continuous heavy precipitation occurred in Huaihe River basin around Meiyu front. The precipitation process on July 2 occurred within the observation range of the two Doppler radar in Fengtai district and Shouxian County. The maximum rainfall of the Meiyu front was over 100 mm in 24 h, so it can be regarded as a typical mesoscale heavy precipitation process related to Meiyu front.

Based on the wind field retrieved from the dual Doppler radar, we find that there are meso–γ scale vertical circulations in the vertical cross–section perpendicular to Meiyu front, the strong upward motion of which corresponds to the position of the heavy rainfall area. Furthermore, other results obtained by this study are identical with the results by analyzing the conventional synoptic data years ago. For example: in the vicinity of 3 km level height ahead of Meiyu front there exists a southwest low–level jet; the rainstorm caused by Meiyu front mainly occurs at the left side of the southwest low–level jet; and the Meiyu front causes the intensification of the low–level convergence in front of it.

Key words: Dual Doppler radar, Meiyu front, Meso–γ scale vertical circulation

1. Introduction

Studies on Meiyu front in the 1970s already have shown that rainstorm and strong convective weather directly related to mesoscale system, and the synoptic scale vertical circulation structure of Meiyu front has been demonstrated (Tao et al., 1979). In addition, there is a large water vapor gradient and a weak wind field convergence zone around the Meiyu front. Meiyu frontal precipitation is often accompanied by the southwest low–level jet, the

①This research was supported by Project HUBEX (Project Number: 49794030) which is funded by the National Natural Science Foundation of China (NSFC).

rainstorm caused by Meiyu front mainly occurs at the left side of the low jet (Zhu et al., 1992). In heavy rainfall cases, Meiyu front can cause precipitation of 100–300 mm a day. In recent years, the cloud clusters, its mesoscale features and precipitation during Meiyu period are studied with the satellite cloud imagery. Now, the internal flow field features of these cloud clusters can be revealed by Doppler radar data.

Many studies have been done previously on Meiyu front precipitation. For example, the significance of lower level jet on heavy precipitation was analyzed in terms of synoptic scale. Matsumoto (1972) studied the dynamic mechanism of the lower level jet; Akiyama (1973) and Zhai, et al. (1999) studied the relationship between the low level jet and heavy precipitation. During the Meiyu period, the low level jet can transport the warm and wet air from the Bay of Bengal to Huaihe River basin and provides the water vapor that heavy precipitation requires. Ninomiya and Akiyama (1992) noted that the interaction of multi–system of various scales plays a very important role in Meiyu precipitation. They made analysis by using surface rainfall data and the satellite cloud imagery data and indicated that the heavy precipitation process in Meiyu front was mainly caused by the meso $-\alpha$ scale precipitation system. Zhu et al. (1994) studied the meso–scale structure of rainstorm in Meiyu front and demonstrated that the lower level cold advection and the surface meso–scale convergence are favorable to the development of rainstorms.

In the past, little has been done on the meso$-\beta$ and$-\gamma$ scale analysis of Meiyu front precipitation because of the limitation of observation facilities. With the development of Doppler radar detecting technology, quite a number of achievements have been obtained as regard to meso scale analysis with Doppler radar data. Ogura et al. (1985) pointed out that convective scale analysis is of great significance to the study of the merging of cloud cluster. They also indicate that the low level convergence in Meiyu period plays an important role in the development of rainstorms. Hor et al. (1998) made a study on the inner air flow structure of Meiyu front in " Taiwan Area Mesoscale Experiment (TAMEX)" by using the airborne radar and demonstrated that the Meiyu front has the characteristics of weak disturbance, low level cold center, etc.

As an effective detecting tool, Doppler radar is able to identify clearly the meso$-\beta$ and $-\gamma$ scale structure that cannot be solved with the conventional weather radar. For example, with the dual Doppler radar, Zhou (1990) made an analysis of the cross–section structure of the across front convection area in one of the Meiyu fronts in " Taiwan Area Mesoscale Experiment (TAMEX)" and found that there existed a strong convergence in the lower layer of troposphere in front of the Meiyu front. Takahashi et al. (1996) analyzed the features of the mesoscale and convective scale of the Meiyu front precipitation in Japan Island with the Doppler radar. They pointed out that the convection gust front leads to the intensification of lower level convergence. In the Huaihe River basin of China, there were no dual Doppler radar data available before the project HUBEX in 1998. Taking the features of the observational area of the two Doppler radar into consideration respectively in Fengtai district and Shouxian County, the present paper mainly analyzed the wind field structure of the lower and middle layers in the Meiyu front during heavy rainfall period on July 2, 1998 with the dual Doppler radar data, in order to study the inner wind field structure and its development in the Meiyu front precipitation process.

2. Data and method

In June and July of 1998, three Doppler radars from Japan that were arranged in the

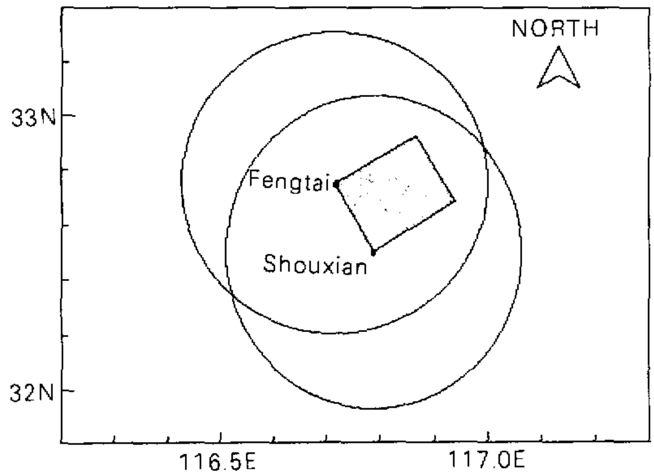

Fig. 1. The positions and the retrieved area (shaded) of the two Doppler radar in Fentai and Shouxian County, with the distance 30 km apart, and the azimuth angle of the Fengtai district–Shouxian County baseline is 157.5° from the north.

HUBEX experiment made observations simultaneously in Huainan City, Fengtai district, and Shouxian County of Anhui Province. Figure 1 shows the locations and the retrieval area of the two Doppler radar in Fengtai district and Shouxian County, and the baseline between them is about 30 km.

With the two Doppler radar detecting at the same time, a three–dimensional wind field can be retrieved from the two meridional speeds relative to two different locations (Ge and Jiang, 1996). Affected by the retrieval error, the wind field retrieved with the two Doppler radar can only be located within a certain range at the both sides of the observational baseline. The retrieved horizontal scope in the present paper is 30 km × 40 km, with the horizontal grid length being 1.5 km. The dual Doppler radar retrieval method used in this paper is able to obtain the three–dimensional wind fields of various height above the ground, with the vertical grid spacing being 0.25 km.

3. Brief description of synoptic situation

Fig. 2 shows the surface synoptic situations from 0200 Beijing Standard Time (BST) 1 July to 0200BST 3 July. At 0200BST 2 July, the Meiyu front was located in the northern part of Anhui province and associated with a mesoscale low. At that time, to the south of the shear line at 700–850 hPa there was a strong southwest low–level jet with a maximum wind speed of 25 m / s, and the mesoscale cyclone was constantly intensified as it moved eastward and caused the heavy rainfall (> 100 mm / day) shown in Fig. 3a. After that, the Meiyu front migrated from north to south across Shouxian County until 0200BST on July 3, and in the southwest area, there was another cyclonic vortex at 700 hPa being developed to be a surface cyclone and moved to Shouxian County. This mesoscale cyclone reached its strongest stage at about 1500BST and its 12–hour (0800–2000BST) rainfall maximum around Fengtai district and Shouxian County was 70 mm (Fig. 3b). Then, the southwest low–level jet weakened and

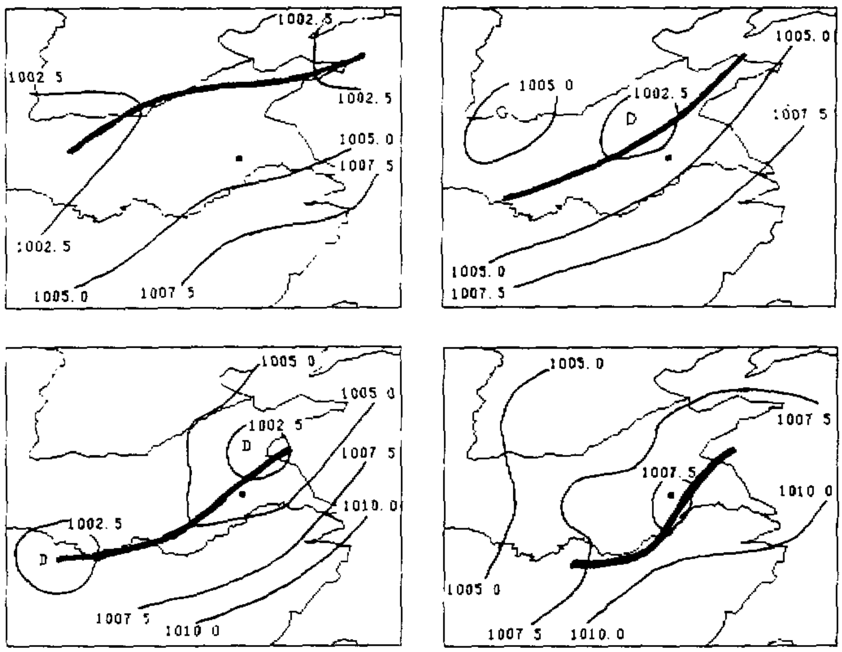

Fig. 2. Surface Weather Charts at 0200 of July 1, 0200, 0800 of July 2 and 0200 of July 3 (Beijing Standard Time), wherein the thick bold line stands for the quasi–stationary front, the small black square represents the location of Shouxian County and the thin bold line stands for the isobar (hPa).

changed into almost southerly wind.

The hourly rainfall at Lixin and Shouxian County of Anhui province is shown in Fig. 3. Lixin is located to the northwest of Shouxian County, and Lixin and Shouxian County are separated by 80 km. Fig. 3a shows maximum precipitation (63.3 mm / h) at Lixin occurred at around 0500BST while heavy rainfall occurred at Shouxian County from 1200 to 1800BST with a maximum of 19.7 mm / h (Fig. 3b). Obviously, the precipitation at Shouxian County was 10 hours later than that at Lixin, indicating that the rainband moved slowly southward associating with the Meiyu front.

4. The evolution of cloud cluster and the features of the wind field

In this section, in order to study the structure and features of the inner wind field of the Meiyu front, we analyze the evolution of the mesoscale convective cloud clusters embedding in the Meiyu front with the conventional weather radar data, then analyze the inner wind field features of the Meiyu front by using dual Doppler radar data.

4.1 *The evolution of precipitating cloud clusters*

The Fuyang radar image (Fig. 4) revealed the mesoscale structure of the cloud cluster.

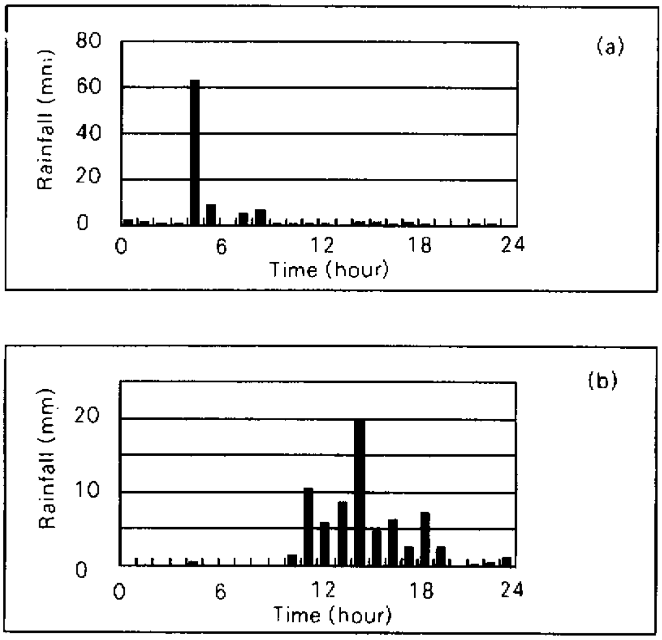

Fig. 3. The hourly rainfall amounts on 2 July 1998. (a) Lixin; (b) Shouxian County.

The cloud cluster formed in the west of Fuyang and directly related to the mesoscale cyclonic vortex. At 0130BST of July 2, the mesoscale cloud cluster was in the area north of Fengtai district and Shouxian County. At that moment, the cyclonic vortex associated with cloud cluster in the west was moving eastward and merging with the south part of the comma–shaped cloud system in the east. Later, the two cloud clusters were completely combined together when further moving eastward and became a mesoscale convective system. Then, the main part of the system moved slowly southeastward and at 0630BST entered the observational area of the two Doppler radar in Fengtai district and Shouxian County (The circles in Fig. 4 indicate the observational range of the two radar). Before 0630BST, the observational area was mainly covered with the rather weak echo (< 20 dbz); since 0630BST, in the north of the observational area there occurred the pretty strong echo; heavy rainfall appeared in the observational area at 1100BST, and the whole observational area was covered with strong echoes which reached its maximum around 1500BST. At this moment, both the two Doppler radar appeared a narrow strong echo (> 21 dbz). This intense rainfall coincided with the strong echo around Shouxian County shown in Figs. 3b and 4. By 1630BST, the main echoes gradually moved out of the detection area and weak echoes occupied the observational area.

4.2 *Wind field analysis*

In order to study the internal structure of the Meiyu front, the middle and lower layer vertical wind field and horizontal wind field structure have been analyzed with the dual

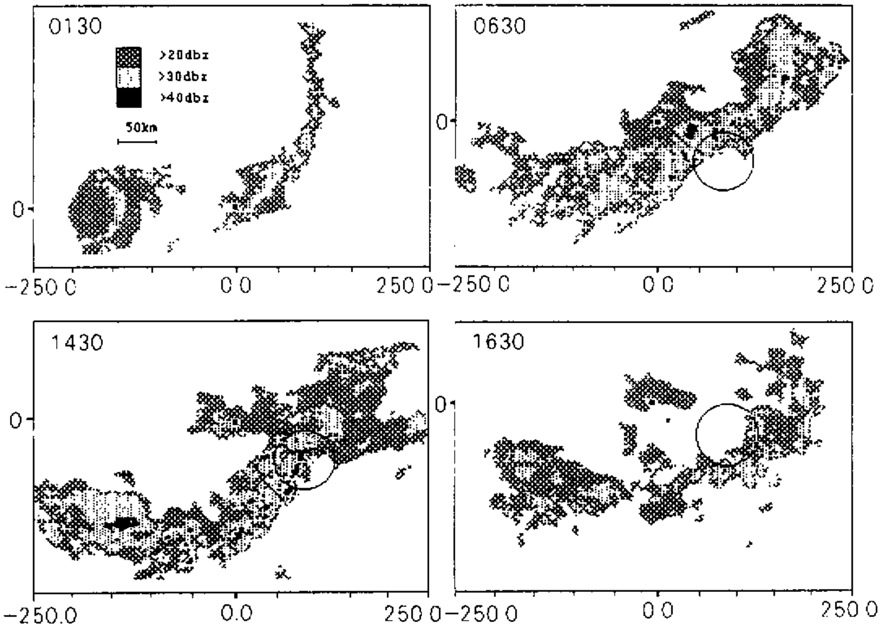

Fig. 4. The conventional weather radar echo at 0130, 0630, 1430 and 1630BST on 2 July 1998 in Fuyang (elevation angle being 0.4°), wherein the circles stand for the observational area of the two Doppler radars, the black square represents Fuyang.

Doppler radar data.

Figure 5 shows the wind field in vertical cross–section on 2 July 1998, observed in the HUBEX period with the dual Doppler radar. We have mentioned above that to the south of the Changjiang River and Huaihe River shear line there was a strong southwest low–level jet. The dual Doppler radar detected this jet at the height of 3.0 km (Fig. 5). Between 2–4 km height, the southwest wind velocity was comparatively homogeneous, with the maximum

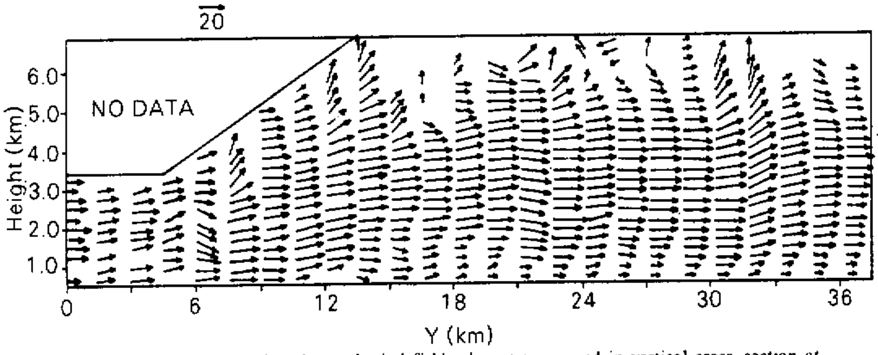

Fig. 5. Dual Doppler radar observed wind field relevant to ground in vertical cross–section at 0230 (Beijing Standard Time) on July 2, 1998. Y–axis is in SW–NE direction from the left to the right.

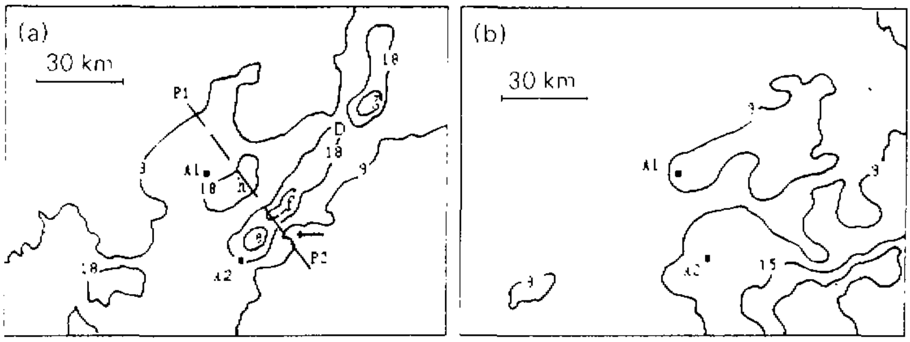

Fig. 6. Doppler radar PPI echo intensity at Fengtai district on 2 July 1998 (the elevation angle being 1.1°), where A1 stands for Fengtai district, A2 stands for Shouxian County, the thin line is the intensity isoline (dbz). (a) 1430BST. (b) 1601BST. Line *P1P2* is the NW–SE cross–section shown in Fig. 7.

speed over 25 m / s; the southwest wind speed reduced quickly above 4 km with large vertical shear of wind velocity, and the northeast wind occurred. After 0730BST, when the convective area in front of Meiyu front approached the observational area, both of the two radar were not able to detect the southwest low–level jet area when the southwest wind gradually changed to almost south wind. When the southwest low–level jet appeared around Fengtai district and Shouxian County, the rainstorm of pretty large area north of Fengtai district occurred. The precipitation at Lixin reached 100 mm, which implies that the rainstorm caused by Meiyu front usually occurs at the left side of the southwest low–level jet.

In the mature stage of Meiyu front, the Meiyu front cloud band with a width of 30 km was along SW–NE direction. There was a narrow strong echo band (rainband) with the average width of 6 km. It is apparent that there were many convective cells (labelled "e" to "g" in Fig. 6a). Behind the strong echo band there was a weak echo transitional zone, and following it was a moderate strong echo area (represented by "h" in Fig. 6a). On the other hand, the convective cell (represented by "e" in Fig. 6a) exhibited moderate reflectivity (>20 dbz) and it indicates that there was the strong convective rainband around Shouxian County. This is the reason why heavy precipitation (19.7 mm / h) occurred at 1400–1500BST (Fig. 3b). It can be seen From Fig. 6b that after the front went across the area, the echo in the observational area weakened and dissipated, and became an echo–free area.

The wind field along the NW–SE cross–section 16 km northeast of Shouxian County (see line *P1P2* in Fig. 6a) is depicted in Fig. 7. The leading edge at surface of the front labelled "D" is located at $y=13$ km. It can be seen from Fig. 7a that Meiyu front has a low height and small slope with active warm air. The warm and wet air coming from the south slid upward along the frontal surface, with the strong echoes occurring in this obliquely updraft. It encountered the cooler air from the north in the lower troposphere at leading edge of the front and caused convergence, thus providing the lifting mechanism at the low level and vapor, and the depth of the cold air associated with the front is about 2 km. This lifting mechanism resulted in a narrow band of convection at the leading edge (Fig. 7b). The convective updraft with a maximum of 8 m / s developed in the high reflectivity region (the "f" cell in Fig. 6a with 20 dbz$<Z<$30 dbz), due to the frontal lifting mentioned previously, which shows that

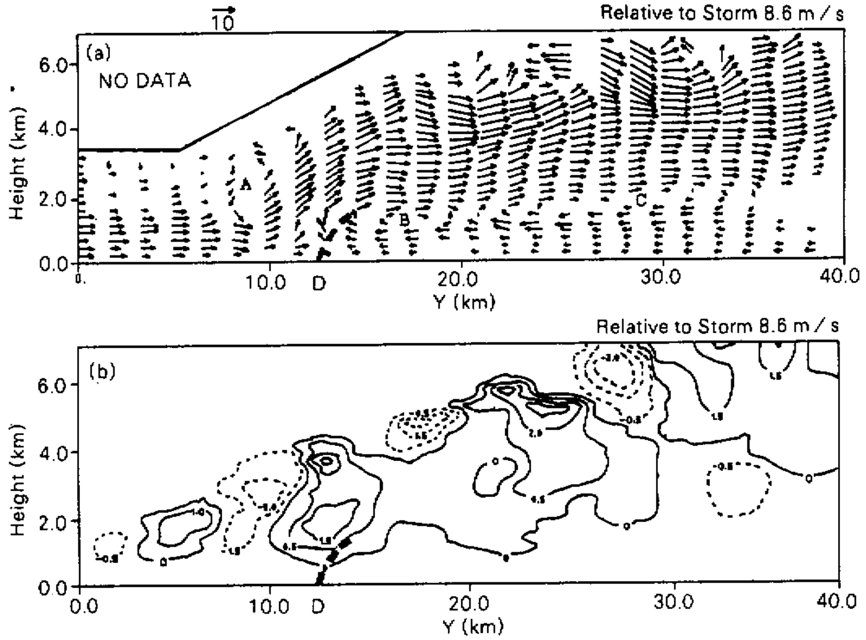

Fig. 7. Perpendicular to Meiyu front vertical cross-section observed with dual Doppler radar at 1430BST on 2 July 1998. (a) wind field related to Meiyu front, (b) vertical velocity distribution (m / s, the solid line indicating upward, the dashed line, downward). *Y* axis is along SE–NW direction from the left to the right, making a 90° angle with the Meiyu front, the cross cut is within the active convection region ahead of the front. A, B, and C respectively stand for the three vertical circulations of meso–γ scale. The location of the surface front is labelled "D".

the front is responsible for initiating and maintaining the convective rainband at leading edge of the Meiyu front and causing the quick increase of precipitation at that time (Fig. 3b). A secondary updraft with a maximum of 6 m / s occurred in the area about 8–14 km north of the leading edge. Its location coincides with the "h" echo (Fig. 6a).

In order to show the links between the wind field in the cross–section and the heavy rainfall, we label "D" in Figs. 6a, 7a and 7b. In Fig. 6a, label "A2" is the position of Shouxian County, along A2—D is the strongest rainfall area, which can be seen from Fig. 3b for hourly rainfall at 1400—1500BST. The same label "D" in Figs. 7a and 7b indicates the position of the surface front maximum upward motion corresponding with the strongest rainfall area A2—D (strongest echo) in Fig. 6a.

We find a noteworthy wind structure that during the mature stage of Meiyu front, there were three meso–γ vertical circulations in the cross–section perpendicular to Meiyu front. From Fig. 7a and Fig. 6a, it can be seen that these vertical circulations have a horizontal scale of 4–15 km, so they are meso–γ systems. They mainly occurred in the lower layer of the convection, with a vertical height of about 3.5 km. In Fig. 7a, the meso –γ scale vertical circulation A is located ahead of the front. In front of the circulation is a downward airflow and behind it is an upward airflow. The downward airflow causes a V–shaped echo gap ahead of the front, as shown by the arrow in Fig. 6a. Whereas the meso–γ scale vertical circulation B further intensified the lower level convergence near the frontal area. The structure of circulation

B is just on the opposite rotating direction to that of circulation A. The upward airflow ahead of it causes the intensification of convection, makes the strong echo zone (the "f" cell in Fig. 6a) appear in the strong upward airflow ahead of it. Behind it the weak downward airflow caused a weak echo transition zone after the strong echo belt, followed by another strong echo zone (the "h" cell in Fig. 6a with 18 dbz< Z< 21 dbz), which was resulted from the upward airflow of meso–γ scale vertical circulation C. All these results clearly indicate that the strong echoes occur in the strong upward airflow of these meso–γ scale vertical circulation.

5. Summary and conclusions

With dual Doppler radar data, the studies on the southwest low–level jet ahead of the Meiyu front and wind field structure in the vertical cross–section perpendicular to the front surface have been discussed in this paper.

The analysis of the Meiyu front structure by dual Doppler radar data reveals that the Meiyu front causes the intensification of lower level convergence ahead of Meiyu front with an upward maximum value area in the Huaihe River basin. This structure is consistent with that of the Meiyu front in Taiwan region obtained by Zhou et al. (1990). Meanwhile, it has been revealed also that Meiyu front has a low front height and small slope with active warm air moving upward along the front. These features found are identical with the Changjiang River and Huaihe River Meiyu front vertical circulation structure demonstrated by Tao et al. (1979) by use of conventional data. During the mature stage of the Changjiang River and Huaihe River Meiyu front, the south component of wind velocity is larger than that of the Meiyu front in Japan Island.

The study in present paper mainly reveals that the precipitation process in 1998 is closely related to the meso–γ scale systems perpendicular to the Meiyu front. These systems are directly related to the formation of heavy precipitation under the large–scale weather pattern of quasi–stationary Meiyu front. The vertical velocity distribution (Fig. 7b) near the front is similar to that of the Meiyu front in Taiwan region obtained by analysis of the aircraft detection as indicated by Hor et al. (1998). The difference of wind structure in vertical cross–section between present study and Zhou et al. (1990) is that in the Changjiang River and Huaihe River Meiyu front there were three meso–γ scale vertical circulation systems while in Taiwan region there was only one vertical circulation. It is probably due to the different stages of the front and geographical influence. After the Meiyu front went away from the observational area of dual Doppler radar in HUBEX, the lower layer meso–γ scale vertical circulations disappeared.

The conclusions are as follows:

1) It is found by using dual Doppler radar data that there were meso–γ scale circulations in the vertical cross–section of Meiyu front in Huaihe River basin. The occurrence of these meso–γ scale circulation systems in the lower troposphere caused the lower layer convergence intensified. Its upward zone was in consistence with the strong echo (convection cells), which indicated that these meso–γ scale vertical circulations were directly relating to the heavy precipitation.
2) There was an obvious southwest low–level jet at 3 km height ahead of the Meiyu front. When it approaches the convective precipitation area of the Meiyu front, it weakened apparently and changed into southerly airflow. The rainstorm caused by it occurred at its left

side. The wind speed of the southwest low level jet at 2–4 km height was very even, and above 4 km, the velocity will decrease quickly with a large vertical shear.

3) When the low level convergence intensified near Meiyu frontal area, it provided the upward airflow and vapor convergence required by the frontal precipitation, thus caused heavy precipitation.

REFERENCES

Akiyama, T., 1973: Ageostrophic low–level jet stream in the Baiu season associated with heavy rainfall over the sea area. *J. Meteor. Soc. Japan*, **51**, 205–208.

Anhui Provincial Meteorological Science Research Institute, 1986: *Diagnostic Predication of Rainstorm in Meiyu Period*, Anhui Science and Technology Press, 1–25.

Ge W. Z., and P. J. Jiang, 1996: *Atmosphere and Ocean Radar Detection*, China Ocean Press, 218–233 (in Chinese).

Hor T. H., M. H. Chang, and B. J. D. Jou, 1998: Mesoscale structure of air flow in a Mei–yu front leading edge observed by aircraft off the east coast of Taiwan during TAMEX IOP 9. *J. Meteor. Soc. Japan*, **76**, 473–496.

Matsumoto, S., 1972: Unbalanced low–level jet and solenoidal circulation associated with heavy rainfall. *J. Meteor. Soc. Japan*, **50**, 194–203.

Ninomiya K., and T. Akiyama, 1992: Multi–scale features of Baiu, the summer monsoon over Japan and the east Asia. *J. Meteor. Soc. Japan*, **70**, 467–495.

Ogura Y., T. Asai, and K. Dohi, 1985: A case study of a heavy precipitation event along the Baiu front in northern Kyushu, 23 July 1982: Nagasaki heavy rainfall. *J. Meteor. Soc. Japan*, **63**, 883–900.

Takahashi N., H. Uyeda, K. Kikuchi, and K. Iwanami, 1996: Mesoscale and convective scale features of heavy rainfall events in late period of the Baiu season in 1988, Nagasaki Prefecture. *J. Meteor. Soc. Japan*, **74**, 539–561.

Tao S. Y., Y. H. Ding, and X. P. Zhou, 1979: Study on rainstorm and strong convection weather. *Scientia Atmospherica Sinica*, **3**, 227–238 (in Chinese).

Zhai G. Q., H. J. Ding, et al. 1999: Diagnostic study of rainstorm weather accompanied with low jet. *Scientia Atmospherica Sinica*, **23(1)**, 113–118 (in Chinese).

Zhou Z. D., J. S. Hong, and X. M. Deng, 1990: Dual–doppler analysis of convective rain belt in the Mei–yu front. *Atmospheric Sciences*, Taiwan, **18**, 239–264 (in Chinese).

Zhu Q. G., J. R. Lin, S. W. Shou, and D. S. Tang, 1992: Principles and Method of Synoptics. China Meteorological Press, 495–509 (in Chinese).

Zhu S. F., M. Zhao, et al. 1994: Mesoscale structure and boundary layer features of Meiyu front rainstorm. *Journal of Nanjing Institute of Meteorology*, **17(1)**, 111–116 (in Chinese).