Dual Doppler Radar Analysis of a Squall Line Observed over the China Continent during the HUBEX Intensive Field Observation

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1. Introduction

The energy and water cycle in the subtropical monsoon region of the East Asia is characterized largely by Baiu/Meiyu front in summer. It is one of subtropical fronts and a unique subsystem of the Asian monsoon. Various scale of cloud/ precipitation systems are formed in this frontal zone and play major role in the energy and water cycle in the zone. One of purposes of GAME/HUBEX (GEWEX Asian Monsoon Experiment / Huaihe River Basin Experiment) is to study the evolution of mesoscale cloud system.

The intensive field observation (IFO) of GAME/HUBEX was performed in the Huaihe River Basin, China during the period from 11 June 1998 to 22 July 1998. Three Doppler radars were installed at Shou-xian, Huai-nan and Feng-tai and performed simultaneous observation (Table 1). During IFO, a significant squall line was observed by the radars. The purpose of this study is to clarify the structure of the squall line developed over the continent.

Houze et al. (1989) showed a conceptual model of the kinematic, microphysical, and radar-echo structure of a mid-latitude squall line. Its characteristic features are the convective line with a trailing stratiform precipitation, the rear-inflow, the front to rear flow and a gust front. Biggerstaff and Houze (1993) showed a vertical motion and trajectory of precipitation particles within a mid-latitude squall line. They found a transition zone between the convective line and a mesoscale stratiform precipitation zone. Johonson and Hamilton (1988) found the pre-squall mesolow in front of a squall line, the mesohigh just behind the convective line and a wake low within the stratiform precipitation area. It is not clear that these characteristic features are found in the squall line which developed in the monsoon environment.

The purpose of this study is to clarify the echo and kinematic structures of the squall line developed over the continent on the basis of the analysis of dual Doppler radar observation.

Shou-xian	116° 46' 58"E	32° 33' 18"N
Feng-tai	116° 42' 10"E	32° 42' 39"N
Huai-nan	117° 01' 10"E	32° 38' 19"N

Table 1: **Locations of Doppler radar observation sites.**

2. Environmental condition

The squall line was began to be observed around 10 UTC, 16 July 1998. It passed over the radars at 1130 UTC and moved northeastward with decaying. The local time of the observation site was advanced for 8 hours to UTC. The squall line, therefore, developed in the late evening as a part of diurnal variation of convectively activities due to strong solar radiation.

The synoptic condition of the squall line development is found in the JMA Global Ob-

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jective Analysis (GANAL). The height field in Fig. 1 shows a mesoscale low, whose horizontal scale was about 1000 km, was located around the observation sites. A westerly or southwesterly was prevailed at Fuyang (indicated by 'Fy' in the figure) and Shouxian ('Sx') at 850 hPa. The relative humidity at Fuyang and Shouxian was larger than 80 % at this level.

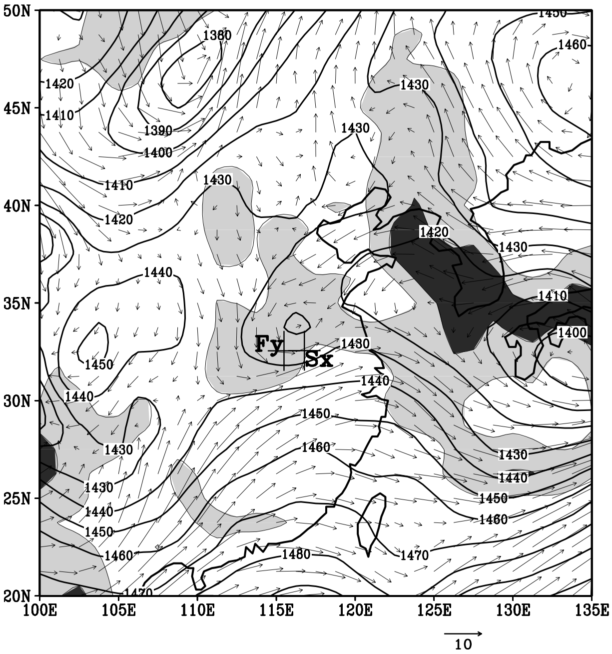

Figure 1: **Height (meter), Relative humidity (lightly shaded areas mean larger than 80 % and darkly shaded larger than 90 %) and horizontal wind (arrows; the scale is shown at the bottom of the figure) at a level of 850 hPa at 1200 UTC, 16 July 1998 obtained from the JMA GANAL. The location of Fuyang observatory is indicated by 'Fy' and that of Shouxian by 'Sx'.**

The mesoscale low had a significant lower-level convergence (Fig.2a) and its vorticity extended from the surface to 350 hPa (Fig.2b). The squall line is considered to be developed in a favorable environment of the lower-level convergence and the positive vorticity associated with the mesoscale low.

A sounding at Fuyang at 1119 UTC, 16 July 1998 (Fig.3) showed vertical profiles of the environment of the squall line. The profile of θ_e shows that the stratification was convectively unstable below 750 hPa (Fig.3a). CAPE of this profile was 1720 J kg−1. This instability was rather smaller than that of an environment of a strong mesoscale convective system. The troposphere was highly humid below 500 hPa and a dry layer was present between 500 hPa and 350 hPa (Fig.3b). The humid condition is one of the characteristics of the environment. Wind direction was almost westerly throughout the troposphere. Wind speed was about 7~8 m s^{-1} below 700 hPa and 11~12 m s^{-1} between 650 and 500 hPa. The vertical wind shear was not so significant (Fig.3c).

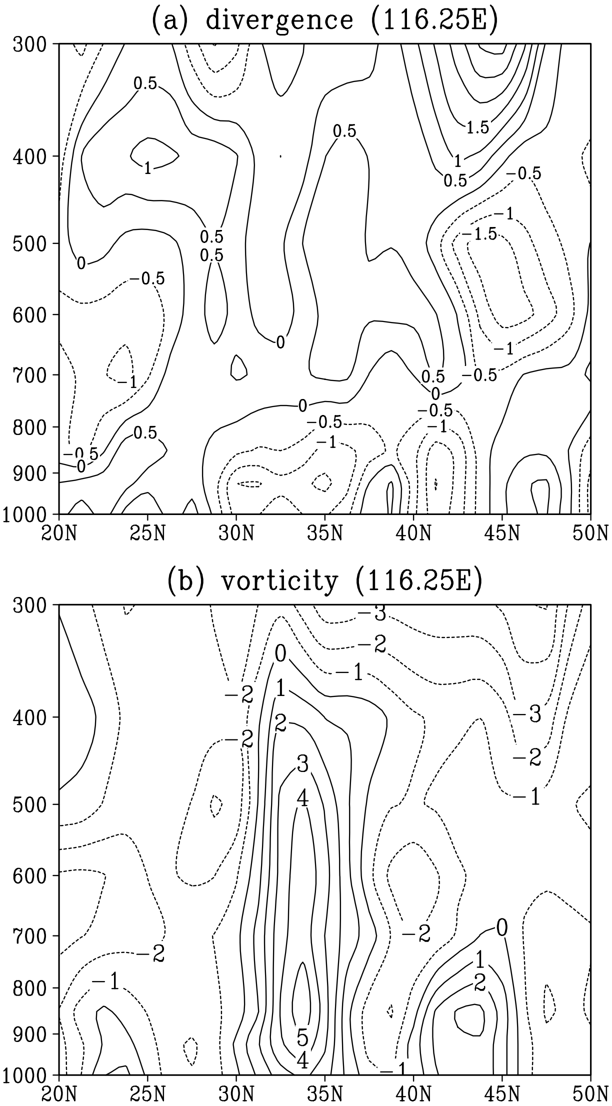

Figure 2: **Vertical cross sections of (a) divergence (unit is $10^{-5}s^{-1}$) and (b) vorticity (unit is $10^{-5}s^{-1}$) along 116.25°E obtained from the JMA GANAL at 1200 UTC, 16 July 1998.**

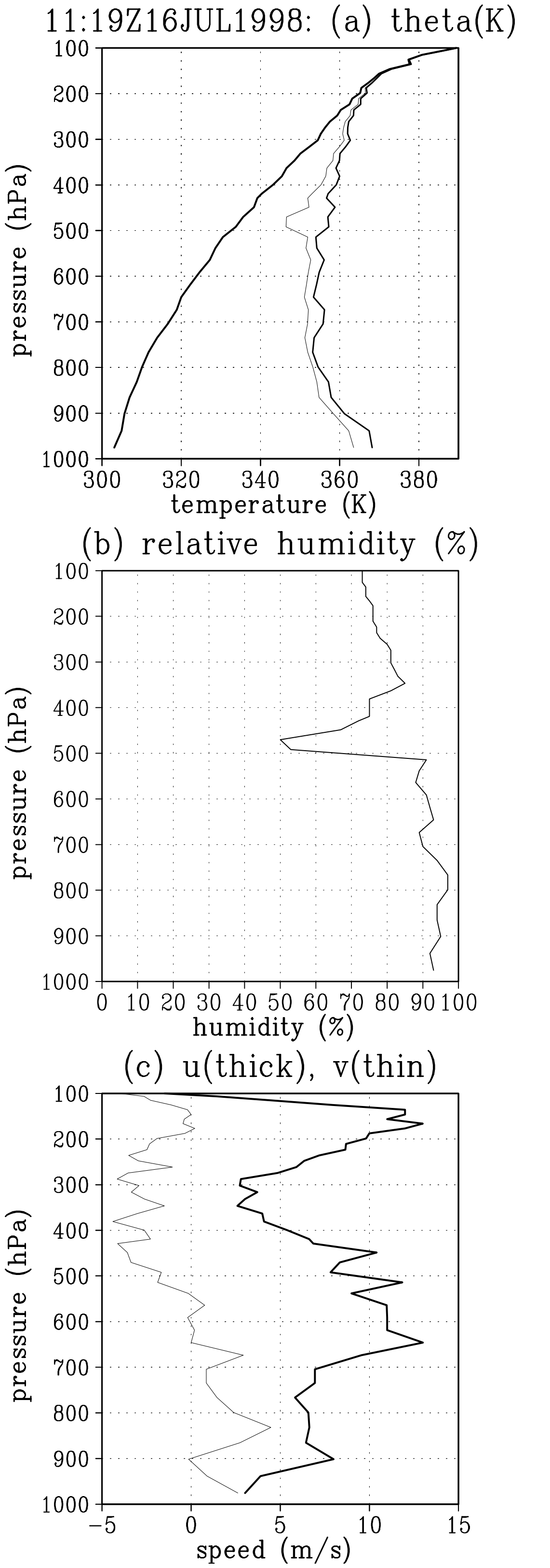

Figure 3: **Vertical profiles of (a) potential temperature, equivalent potential temperature and saturated equivalent potential temperature (K) (b) relative humidity (%) and (c) zonal and meridional wind velocities (m s^{-1}) at 1119 UTC, 16 July 1998 observed at Fuyang.**

3. Characteristics of cloud

Infra-red images of the Geostationary Meteorological Satellite (GMS) shows that a low Tbb cloud associated with the squall line developed near Shouxian (Fig.4). Before the squall line cloud developed, an intense and large cloud cluster developed to the west of the squall line. The squall line cloud begin to develop at 1027 UTC (Fig.4a) at 116°E and 32.5°N to the west of Shouxian. It moved eastward with development (Fig.4b) and merged with the cloud which was located to the east of the squall line (Fig.4c). The squall line was almost in mature stage in Fig.4b and decaying stage in Fig.4c.

4. Doppler radar observation

The squall line was formed outside of the Doppler radar observation range and approached the radars from the southwest around 10 UTC, 16 July 1998. It passed over the radars at 1130 UTC and moved northeastward with decaying. The squall line extended from the northwest to the southeast with a width of a few tens kilometers. The CAPPI display of radar echo showed that the squall line consisted of intense convective cells and its leading edge was very much clear (Fig.5). Most convective cells were located along the leading edge. Some of cells reached to a height of 17 km.

Horizontal velocity at a height of 2 km was almost southwesterly, which was found in the environmental wind (see Fig.1). The magnitude of the horizontal velocity is rather larger than that of the environment. The acceleration of horizontal velocity was caused by the intense convective activity of the squall line.

The relative velocity which calculated by subtraction of the movement velocity of the squall line from the wind velocity is shown in Fig.6. The relative velocity had a component parallel to the squall line. This parallel component was significant throughout the troposphere when the squall line was extending.

When the squall line was approaching the radar, new cells was formed successively on the southeasternmost part of the squall line. Consequently, the squall line extended southeastward. The parallel component had a vertical shear and its down-shear direction was the southeast. The new cells was formed on the down-shear side of the parallel component.

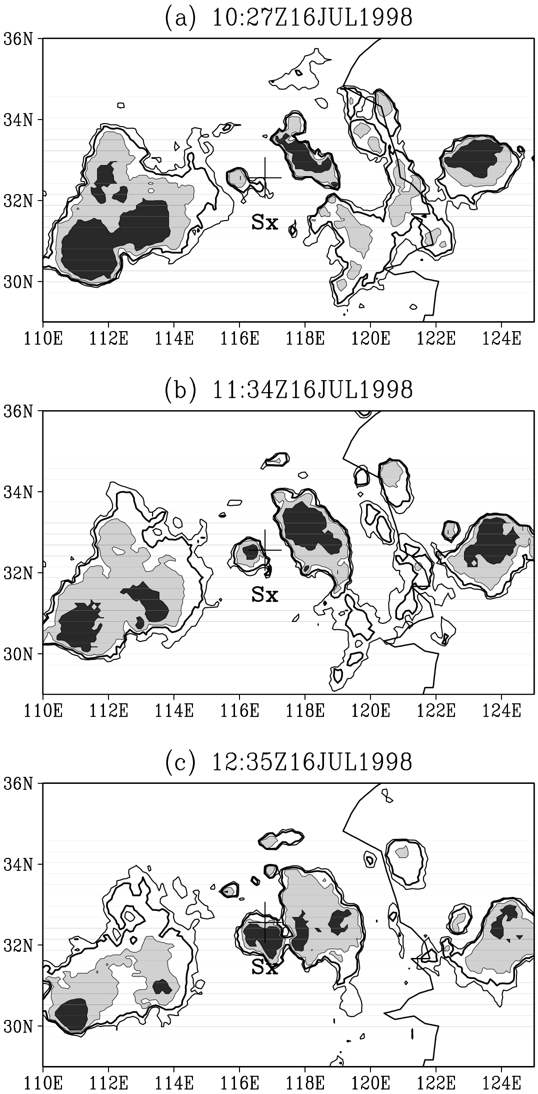

Figure 4: **Time series of GMS IR1 images at (a) 1027 UTC, (b) 1134 UTC, and (c) 1235 UTC, 16 July 1998. The darkly shaded areas indicate Tbb lower than −65°C, the lightly shaded area lower than −55°C, the thick contour lines are −45°C and thin contour lines −35°C. The cross at the central part of each figure indicates the location of Shouxian observatory.**

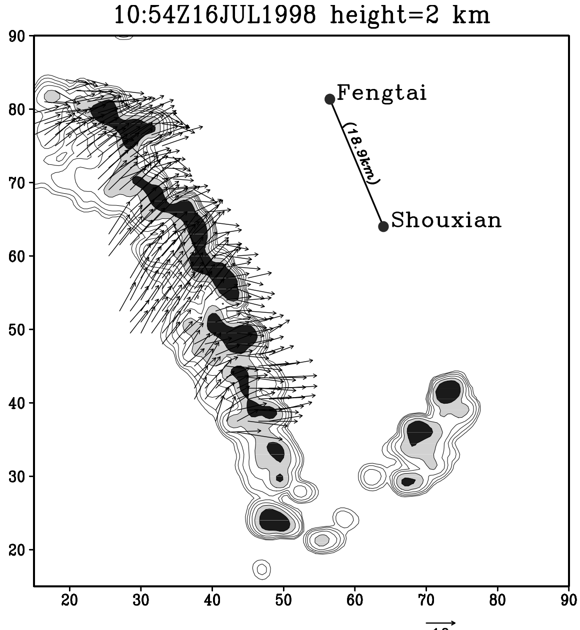

Figure 5: **CAPPI display of echo intensity and horizontal velocity at a level of 2 km at 1045 UTC, 16 July 1998. Darkly shadings indicate 35 dBZ and lightly shadings 30 dBZ. Contour lines are drawn every 5 dBZ from 10 dBZ.**

After the squall line passed over the radar sites, a stratiform precipitation was extending behind the convective leading edge (Fig.7). A new small squall line developed behind the main squall line. The new line was extended along the same direction of the main squall line. A parallel component of the relative velocity was also significant along the new squall line.

In order to examine if the parallel component was present in the environmental wind, we rotated the coordinate to be parallel and normal with respect to the squall line. Figure 8 shows normal and parallel components of the environmental wind. The parallel component v has a significant vertical shear below the level of 450 hPa. This component and its vertical shear are considered to be important for the formation and extension of the squall line.

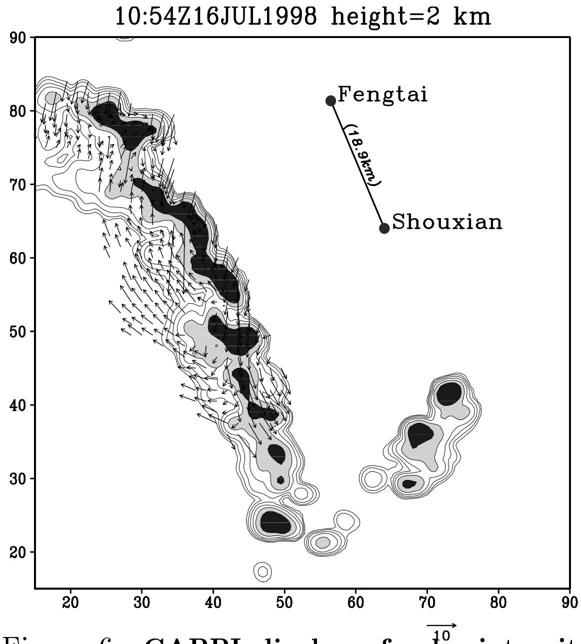

Figure 6: **CAPPI display of echo intensity and horizontal velocity relative to the movement of the squall line at a level of 2 km at 1045 UTC, 16 July 1998. Darkly shadings indicate 35 dBZ and lightly shadings 30 dBZ. Contour lines are drawn every 5 dBZ.**

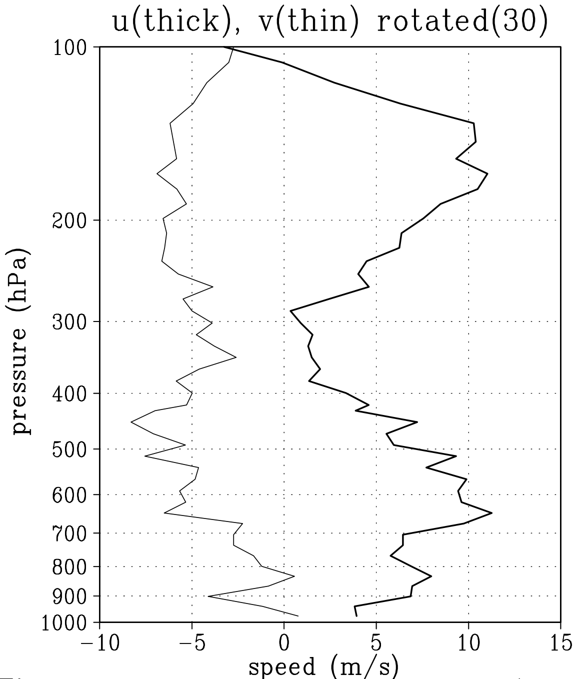

Figure 8: **Vertical profiles of normal (thick line) and parallel (thin line) components of the environmental wind observed by the sounding at Fuyang at 1119 UTC, 16 July 1998. The rotation angle of the coordinates was 30 degree.**

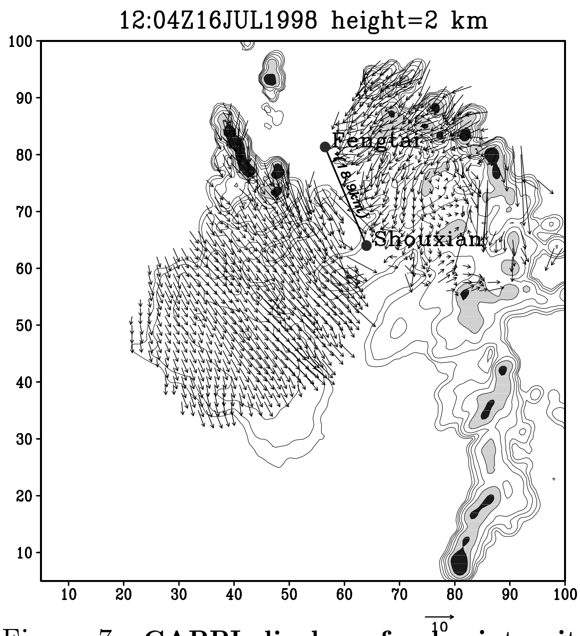

Figure 7: **CAPPI display of echo intensity and horizontal velocity relative to the movement of the squall line at a level of 2 km at 1204 UTC, 16 July 1998. Darkly shadings indicate 35 dBZ and lightly shadings 30 dBZ. Contour lines are drawn every 5 dBZ from 10 dBZ.**

Vertical cross sections of echo intensity and u, w (Fig.9) show a successive development of convective cells at the leading edges. An old cell began to decay at 1033 UTC, then a new cell began to develop. The new cell significantly developed at 1040 UTC and the replacement of convective cell occurred at the leading edge. The successive development maintained the squall line. Consequently, the squall line advanced to the northeast.

The vertical cross section of echo intensity observed by RHI scan normal to the squall line showed that the convective cell at the leading edge was reached to a height of 8 km and a weaker echo extended to about 16 km in height behind the convective cells (Fig.10a). Doppler velocity showed that a strong forward flow was present whose velocity was larger than 13 m s^{-1} at a level of 4 km (Fig.10b). This is a significant rear-inflow to the squall line. The axis of the maximum of the rear-inflow was descended behind the leading edge. Another maximum of a forward flow was present below a height

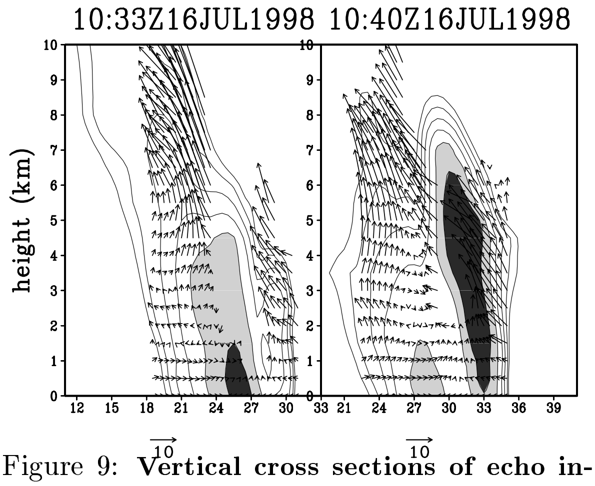

Figure 9: **Vertical cross sections of echo intensity and velocity in the section at 1033 and 1040 UTC, 16 July 1998. The horizontal component of velocity is relative to the movement of the squall line. Darkly shadings indicate 35 dBZ and lightly shadings 30 dBZ. Contour lines are drawn every 5 dBZ from 10 dBZ.**

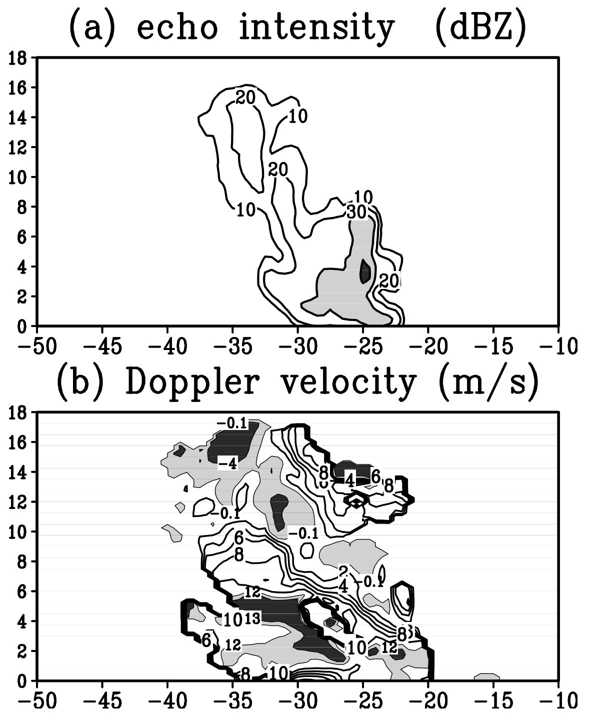

Figure 10: **RHI display of (a) echo intensity and (b) Doppler velocity at an azimuth of 235° at 1100 UTC, 16 July 1998.**

of 2 km. The negative Doppler velocity which was indicated by shadings in the upper levels means rear-ward flow in the upper levels. The axis of rear-ward flow was inclined to the rear of the squall line. The lower-level convergence at the leading edge and the upper-level divergence behind the leading edge were significant.

Time-distance cross sections at two different levels shows that the squall line moved almost at a constant speed of 11 m s^{-1} during the observed period (Fig.11). Individual convective cell developed at the leading edge was almost stationary. New cells developed successively in front of the older cells. Consequently, the squall line moved to the northeast. Some of the convective cells occasionally developed higher than 8 km.

5. Summary and conclusion

A significant squall line was observed by Doppler radars during the intensive field observation of HUBEX. The squall line was formed within the circulation of a mesoscale low. The southwesterly was prevailed while its vertical shear was weak. The lower troposphere was highly humid and moderately convective unstable.

The squall line was extended from the northwest to the southeast and was maintained for longer than two hours. Dual Doppler radar analysis revealed the echo structure and the characteristics of the flow field of the squall line. The squall line was composed of intense convective cells along the leading edge. After it passed over the radar, a stratiform region was observed behind the convective leading edge. The convective cells at the leading edge were reached to a height of 8 km and a weaker echo extended to about 15 km in height behind the convective cells. The squall line was tilted to the up-share side. The rear-inflow was significant at a height of 4 km with a maximum velocity of 13 m s^{-1}. Another maximum of the forward flow was present at the surface. The squall line advanced as a result of the successive development of convective cells at the leading edge.

The parallel component of the wind velocity was significant and had a vertical shear. This component was present in the environmental wind revealed by the rotation of the coordinate. We infer that the parallel component and its vertical shear were important for the formation of the squall lines.

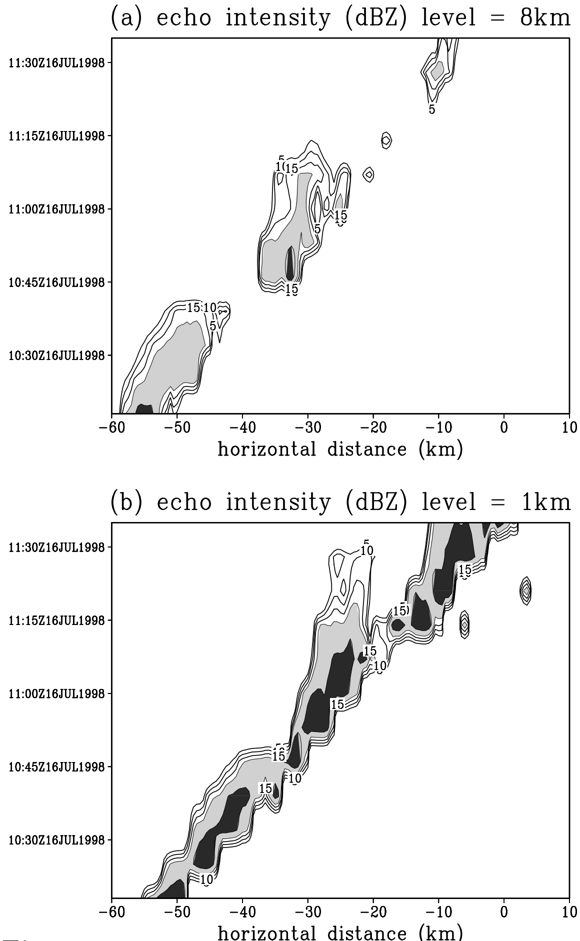

Figure 11: **Time-distance cross sections of echo intensity at an azimuth of 235° at a height of (a) 8 km and (b) 1 km composited from RHI scans.**

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