MESO–α–SCALE STRUCTURE OF TWO RAINBANDS OBSERVED OVER EAST CHINA SEA DURING X–BAIU–99

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1. Introduction

Recent years, a few meso scale observation projects of the Meiyu/Baiu frontal precipitation systems have been conducted (TAMEX, GAME/HUBEX etc). During X–BAIU–99 which was conducted in southwestern Kyushu, Japan, many oceanic precipitation systems developed over East China Sea were observed (Yoshizaki et al., 2000). Moteki et al. (2000) investigated a case of merged two rainbands on 27 June 1999 during X–BAIU–99. Meso–β–scale airflow structure and rapid development processes of this case have been made clear by dual Doppler analyses and numerical simulations. Meso–β–scale airflow structures and development processes of many precipitation systems have been well understood by each meso scale observation project.

For understanding the Baiu frontal precipitation systems, which have the multi scale structure (Ninomiya and Akiyama, 1992), it is necessary to investigate meso–α–scale three-dimensional structure of moisture source fields. However, it is very difficult, in particular over ocean, that we obtain observational data of moisture and thermodynamic fields with high temporal and spatial resolution. To understand meso scale development of the Baiu frontal precipitation systems, both processes of water vapor supply and strengthening the low-level convergence associating with thermodynamic structure must be clarified. A 20 km-resolution RSM (regional spectrum model) and a 5 km-resolution MRI-NHM (Meteorological Research Institute nonhydrostatic model) are great useful for the investigation of moisture and thermodynamic structure in and around the precipitation systems.

In this study, three-dimensional structure of the 27 June 1999 merged two rainbands is investigated by making numerical simulations with the RSM and the MRI-NHM in the point of synoptic and meso–α–scale view.

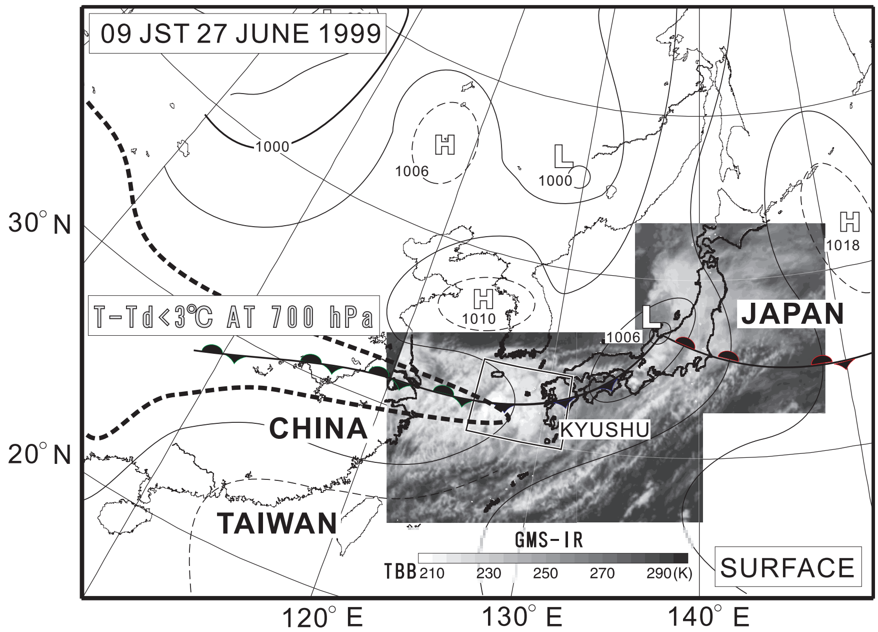

Fig. 1. The surface weather map at 09 JST on 27 June 1999. Wet area (T - Td < 3 °C) at 700 hPa indicated by the dashed line and infrared image with the GMS around the Baiu front are superimposed. The box is the domain of three C-band radars composite image.

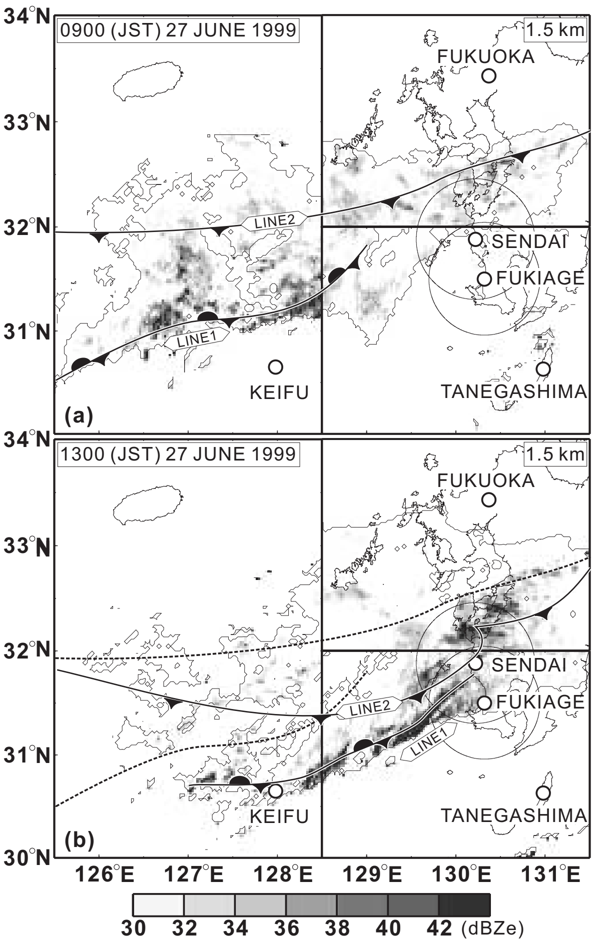

Fig. 2. Horizontal cross sections of reflectivity composite image with three C-band weather radars at (a) 0900 JST and (b) 1300 JST. The dashed lines shown in (b) represent the location of two rainbands at 0900 JST. Two circles indicate Doppler radar observation ranges.

2. Model description

The RSM of the operational model in Japan is a 20 km-resolution regional hydrostatic model. Its horizontal domain has 129 $\times$ 129 grid points. The results of the RSM forecast are used to describe the synoptic structure. The 5 km-resolution MRI-NHM (Saito et al., 2001) is one-way nested within the RSM forecast started at 21 JST 26 June 1999. The horizontal domain has 200 $\times$ 200 grid points. The initial and lateral boundary data were provided from output of the RSM. The 9-hour forecast of the RSM (valid at 06 JST 27 June 1999) is used as the initial condition for the nested 5km-NHM with 9 hours integration time.

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3. General description of two rainbands

Figure 1 shows the surface weather map at 09 JST on 27 June 1999, about 4 hours before the merging and rapid development of two rainbands. The Baiu front moved slowly southward from 26 June to 28 June near the Kyushu island, and precipitation areas formed continuously in the Baiu frontal region. The middle-level humid region (T - Td < 3 $°C$), called "moist tongue", extended from China continent to western sea of Kyushu. A broad cloud area associated with the Baiu front is shown over East China Sea. Low black body temperature area is shown around the east head part of the "moist tongue".

Figure 2 shows horizontal cross sections of reflectivity composite image with three C-band radars (r = 250 km) at Fukuoka, Tanegashima and Keifu-maru in the box of Fig. 1. A southern rainband, called LINE1 (Fig. 2a), is quasi-stationary in the north-south direction but moves eastward. A synoptic frontal rainband, called LINE2, is located in the north of 32° N in a west-east orientation. LINE2 moved southward a distance of about 100 km in 4 hours (Fig. 2b). Then, LINE2 merges to the northeastern part of LINE1 at 1300 JST, and LINE1 develops rapidly.

4. Synoptic moisture fields

Figure 3 shows mixing ratio of water vapor q_v at the surface and 700 hPa with the 12-hour forecast of the RSM (valid at 09 JST on 27 June 1999). At the surface, a southwesterly moist area extends from eastern sea of Taiwan to western sea of Kyushu (Fig. 3a). A strong rainfall area over 5 mm h^{-1} including the northern rainband LINE2 locates at the northeast head of the southwesterly high q_v (> 18.5 g kg^{-1}) area. In the south of a synoptic front, a weak rainfall area, which corresponds to the southern rainband LINE1, is shown in southwestern sea of Kyushu with 200-300 km long. At 700 hPa, an area of high q_v over 8.5 g kg^{-1}, which is consistent with the middle-level humid region of T - Td < 3 $°C$ shown in Fig. 1, extends from China continent to Kyushu island along the synoptic front (Fig. 3b). A front at 700 hPa defined as a synoptic wind shear line (indicated by a symbol of white stationary front in Fig. 3b) locates 150-200 km north of the surface front over China continent and East China Sea. It is found that the synoptic frontal surface is gentle

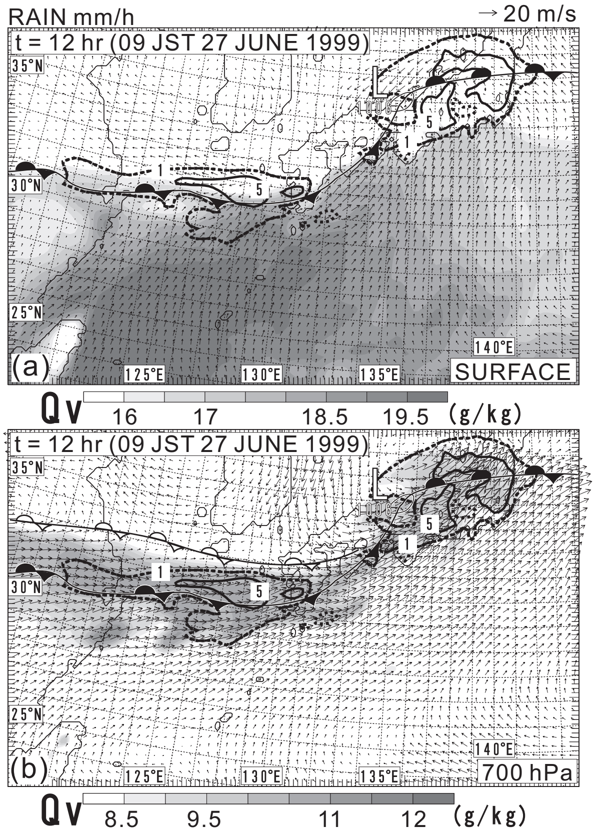

Fig. 3. Mixing ratio of water vapor at t = 12 hr (valid at 09 JST 27 June 1999), (a) at the surface and (b) at 700 hPa reproduced by the RSM. Rainfall area is indicated by contours (1 mm h^{-1}: the dotted contours and 5 mm h^{-1}: the solid contours).

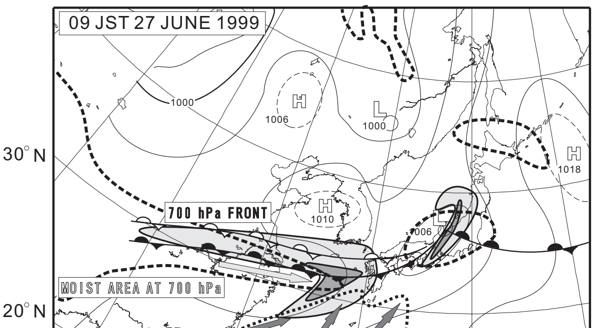

Fig. 4. Schematic diagram of synoptic structure of the Baiu front at 09 JST 27 June 1999. The shaded area indicates rainfall area deduced from infrared image with the GMS and the output of the RSM. The wet areas at the surface (the dotted line) and at 700 hPa (the dashed lines) are shown. The white stationary front indicates the 700 hPa front.

in the west of Kyushu. Although the westerly high q_v area, called "moist tongue", can not certainly induce development of heavy rainfall (Ninomiya, 1978), its large q_v is to condensate again to some extent on the gentle slope of the synoptic front. It is possible that westerly large q_v flux in the layer near 700 hPa contributes to form and maintain a stratiform precipitation area in the north of the synoptic front.

Figure 4 presents a schematic diagram of synoptic structure around the Baiu frontal region based on the surface weather map shown in Fig. 1. The synoptic front has a gentle slope with a broad stratiform region over East China Sea. The southwesterly moist area extending from eastern sea of Taiwan at the surface and a westerly moist area at 700 hPa extending from China continent, are coming across over East China Sea in the western Kyushu. Two convective rainbands of LINE1 and LINE2 is embedded in an intense rainfall area (indicated by dark shading) over East China Sea.

5. Meso–α–scale structure of two rainbands

Figure 5 shows predicted rainfall area and potential temperature θ fields with the 5km-NHM. At t = 4 hr (10 JST), the northern rainband LINE2 forms along a strong convergence line associated with the synoptic front (Fig. 5a). Intense rainfall of LINE2 is very locally (less than 100 km long) in spite of a long length of the synoptic front. The southern rainband LINE1 forms along a weak convergence line, which has little θ contrast but large water vapor contrast (see Moteki et al., 2000), in a southwesterly wind field. We call the weak convergence line developed LINE1 "water vapor front". A meso–α–scale cold pool indicated by closed contours of θ (293 K and 294 K) is shown in the north of the synoptic front. This meso–α–scale cold pool expands greatly at t = 7 hr (13 JST); closed 293 K contour is doubled in area (Fig. 5b). The synoptic front (LINE2) moves southward associated with the cold pool southward expansion. Then, the "water vapor front" (LINE1) and the synoptic front (LINE2) are combined. Rainfall intensity of LINE1 increases greatly from 1-20 mm h^{-1} to 30-50 mm h^{-1} with a length of over 200 km.

Figure 6 shows vertical cross sections of θ, mixing ratio of rain water q_r and water vapor q_v along A-A' and B-B'. In both panels, downward motions and the cold pool with the depth of about 1 km are shown in the north of LINE2. Along A-A', the head of the southwesterly moist airmass

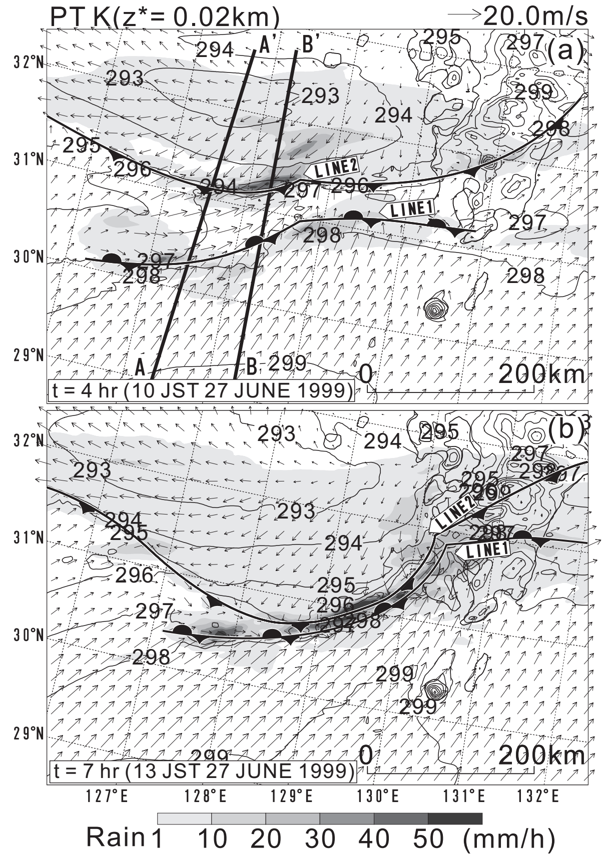

Fig. 5. Rainfall area and wind vectors reproduced by the 5km-NHM at the height of 0.02 km (a) at t = 4hr (10 JST) and (b) at t = 7 hr (13 JST). Rainfall area (shaded) and potential temperature (contours) are shown.

(indicated by dashed contours) locates at LINE1, and q_r in LINE2 is only about 2 g kg^{-1} (Fig. 6a). On the contrary, along B-B', the southwesterly moist airmass reaches up to LINE2, and then q_r in LINE2 is over 4 g kg^{-1} (Fig. 6b). These structures indicate that the southwesterly moist airmass below about 1.5 km has a considerable contribution for the development of LINE2 before the merging with LINE1. As a high q_v air associated with the southwesterly moist airmass was locally supplied to the synoptic front, the length of LINE2 was short (< 100 km). However, these results raise a significant question; why does the head of the southwesterly moist airmass (the "water vapor front") locate at LINE1 along A-A' and reach up to LINE2 along B-B'?

Figure 7 shows vertical cross sections of relative humidity Rh along A-A' and B-B'. The boundaries of two moist airmasses (represented by the thick solid lines) are defined by considering horizontal wind directions in areas of relative humidity larger than 90 %. In both panels, the vertical

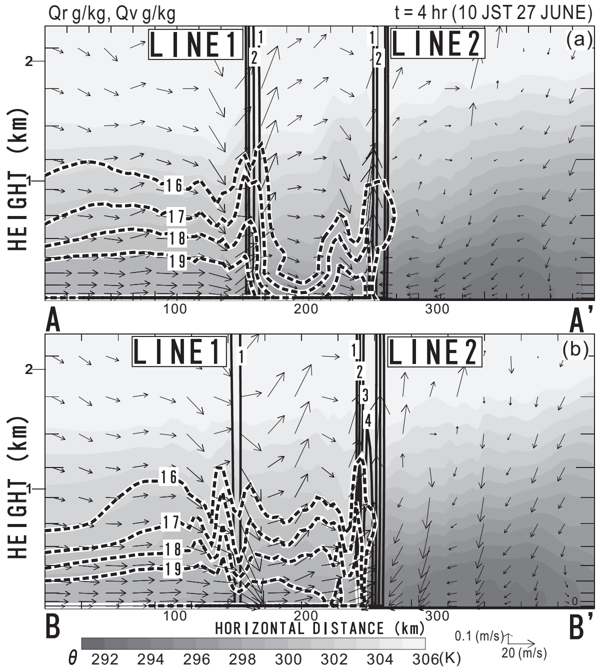

Fig. 6. The vertical cross sections along (a) A-A' and (b) B-B' indicated in Fig. ??(a). Potential temperature (shaded), mixing ratio of rain (contours) and mixing ratio of water vapor over 16 g kg^{-1} (dashed contours) are shown.

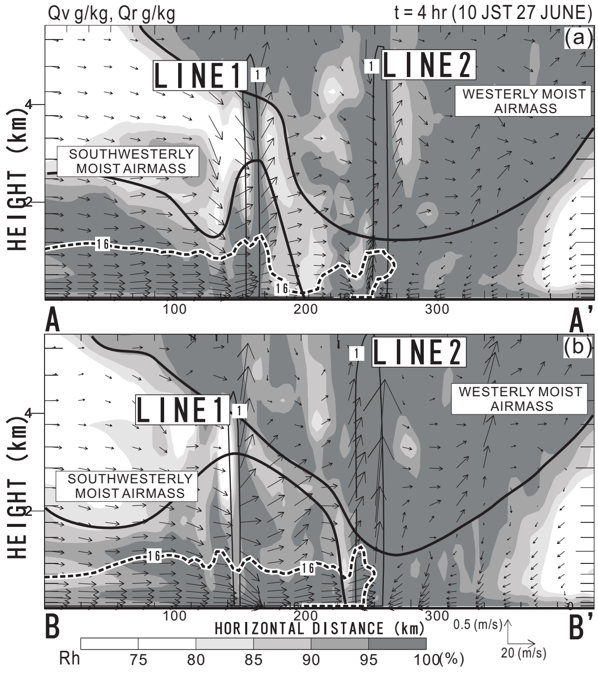

Fig. 7. The vertical cross sections along (a) A-A' and (b) B-B'. Relative humidity (shaded), the solid contours of mixing ratio of rain of 1 g kg^{-1} and the dashed contours mixing ratio of water vapor of 16 g kg^{-1} are shown. The thick solid lines represent the boundaries of the moist airmasses.

mixing layer with the westerly wind ("moist tongue") is shown in the north of LINE1. Along A-A', the southwesterly moist airmass is blocked by the westerly moist airmass of "moist tongue" because these two distinct moist airmasses can not be mixing in horizontal (Fig. 7a). On the contrary, along B-B', the southwesterly moist airmass reaches up to LINE2 because the westerly moist airmass becomes narrow below 2 km (Fig. 7b). Therefore, the location of the head of the southwesterly moist airmass is determined by the location of the blocking in the south edge of the westerly moist airmass. The weak convergence line associated with the "water vapor front" is formed by the confluence of the westerly moist airmass and the southwesterly moist airmass.

In many previous synoptic studies using coarse resolution data, it is recognized that the Baiu front characterized a weak temperature contrast and a strong moisture contrast. The present study using the high resolution model of the MRI-NHM reveal that there is the "water vapor front" with a strong moisture contrast in a southwesterly wind field. The "water vapor front" form in the south of the synoptic front with a weak temperature contrast with a distance less than 100 km.

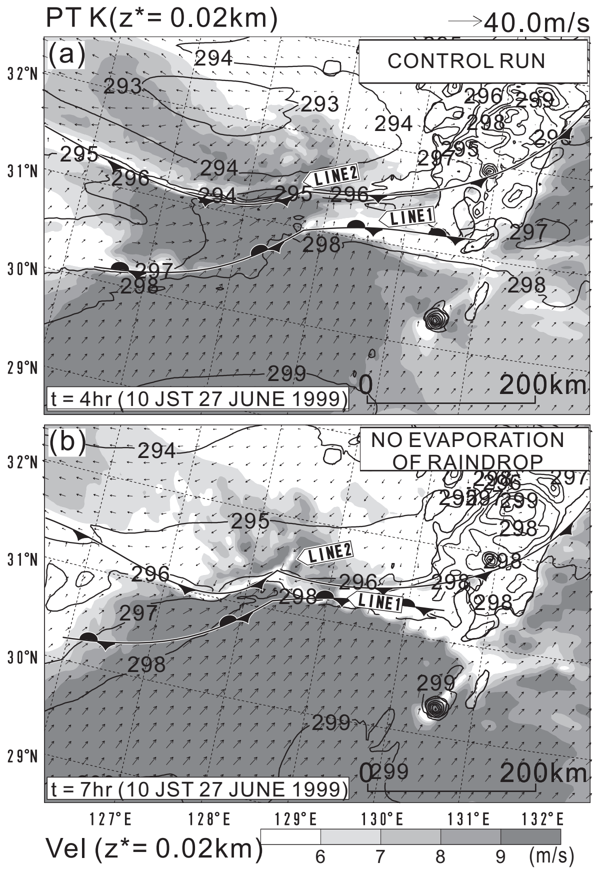

Fig. 8. Horizontal wind velocity fields t = 4 hr (10 JST), at the height of 0.02 km simulated in experiment (a) CNTL and (b) NOEVP. The contours indicate potential temperature.

6. Cold pool effects on development of two rainbands

There are several reports of which a cold pool has important roles for maintenance and motion of the Baiu frontal precipitation systems (Nagata and Ogura, 1991). In order to investigate effects of the cold pool shown in the north of the synoptic front, a sensitivity experiment with the 5km-NHM without evaporation of raindrops, called NOEVP, is executed adding to a control experiment called CNTL. NOEVP is nested from the 6-hour forecast of the RSM (valid at 03 JST 27 June 1999) before the cold pool formed.

Figure 8 shows horizontal wind velocity fields with CNTL and NOEVP at the lowest level ($z^* = 0.02$ km). In the result of CNTL, an area of intensified wind velocity is shown along the south edge of the cold pool (Fig. 8a). This strong northerly wind has the width of over 400 km in a west-east direction. Along the south edge of the cold pool, the synoptic frontal convergence strengthens at the low-level. On the contrary, in the result of NOEVP, the cold pool and an area of intensified northerly wind velocity don't appear in the north of the synoptic front (Fig. 8b).

It is found that the cold pool development has two effects on the synoptic front. First, the cold pool expansion induces the rapid southward motion of the synoptic front. Second, the cold pool development strengthens the synoptic frontal convergence line with the length over 400 km.

7. Conclusions

A conceptual model of meso-α-scale structure of two rainbands on 27 June 1999 is shown in Fig. 9. A broad stratiform region in the north of LINE2 is maintained by a steady supply of water vapor with the westerly moist air. The cold pool is formed by evaporative cooling in the stratiform region. Its great expansion induces rapid southward motion and strengthening convergence of the synoptic front. The weak convergence line in a southwesterly wind field associated with the "water vapor front" is formed by the confluence of the westerly moist airmass above 1.5 km and the southwesterly moist airmass below 2 km.

Along the synoptic front, there was a strong low-level convergence. The cold pool development was great effective on the strengthening convergence of the synoptic front. But a large supply of water vapor with the southwesterly moist airmass was blocked at the "water vapor front". The most of the water vapor was supplied into the southern rainband LINE1. The "water vapor front", which formed in the southwesterly wind field, had a large supply of water vapor, but its low-level convergence was quite weak comparing to the synoptic front. The combining process of two fronts associated with the cold pool development induced simultaneously a great increase of water vapor flux and a strengthening low-level convergence. It resulted that a long length and intense rainband developed rapidly.

In the Baiu frontal zone over East China Sea, it is found that the "water vapor front" form in the south of the synoptic front. It is very effective for a rainfall intensifying rapidly that the synoptic front combines with the "water vapor front".

One of the most important next subjects provided by this study is that origins of two fronts and processes after their combining is clarified. It should be useful to understand origins and evolutions of a previous or next precipitation system in the Baiu frontal zone.

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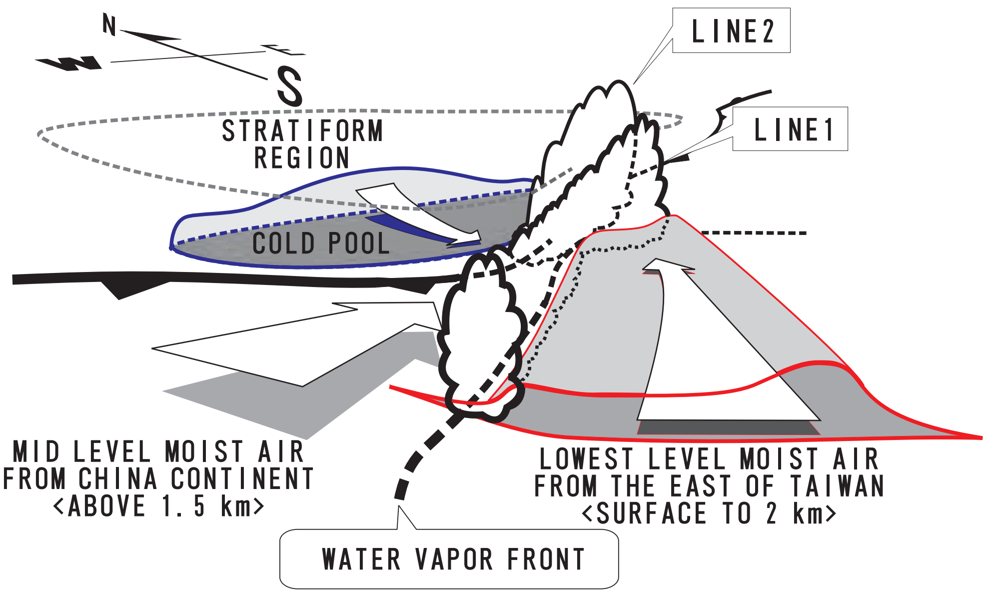

Fig. 9. Conceptual model of meso α scale structure of two rainbands on 27 June 1999. Cold pool formed in the north of LINE2 is indicated by the dark shaded area. The light shaded area in the south of LINE1 shows the southwesterly moist airmass. The convergence line developed LINE1: "water vapor front" is indicated by the dashed line. The westerly arrow along the synoptic front indicates the middle-level moist airflow.