Analytical and Numerical Studies on Meso- β scale Precipitation Bands Observed over Southern Kyushu on 7 July 1996

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Abstract

Three types of meso- β scale bands in a precipitation system over southern Kyushu on 7 July 1996 were analyzed using output from numerical models and observational data from both the Japan Meteorological Agency (JMA) and the Torrential Rain Experiment (TREX).

Four meso- β scale regions comprised the precipitation region of the system. Region 1 was characterized by a unidirectional wind environment in which several short convective bands were organized. Convective cells in these short bands displayed characteristics of back-building cells. A hook-shaped band developed over western part of region 1 where intense outflow from another precipitation region intruded. Another meso- β scale band was simulated in precipitation region 2. In this region, mid-level flow advected convective cells downwind as high equivalent potential temperature air entered the band from its flank, maintaining convection along the whole band length.

Comparisons of airflow structures and band shapes suggest that the mid-level wind direction plays a lead role in determining the type of meso- β scale band. In addition, cold air outflow from other meso- β scale precipitation regions can influence band shape.

1. Introduction

The Baiu front is a stationary front extending from southern China to Japan in early summer. Precipitation systems in the Baiu front have multiple scales. Meso- α scale (~ 1000 km) low-pressure systems develop along the Baiu front, and these low-pressure systems contain meso- β scale (~ 100 km) precipitation regions. Meso- γ scale (~ 10 km) convective cells comprise the meso- β scale precipitation regions (Ninomiya and Akiyama, 1992; Ogura, 1997). Meso- γ convective cells often compose the persistent convective bands that cause floods and landslides (Ogura, 1999). Data from meteorological satellites and radar, and output from numerical models, have been used to analyze convective bands causing such severe meteorological conditions. The analyses have revealed several types of persistent precipitation bands.

Back-building cells comprise one type of persistent

precipitation band. Precipitation bands of this type are composed of several convective cells that form in a straight line. In this line-shaped band, convective cells generate repeatedly at the tip of the band and move along the band. Individual cells move at about the same speed as the mid-level flow, but the band propagation speed is generally slower and large amounts of precipitation can accumulate, causing floods and landslides. Operational meteorological data from the Japan Meteorological Agency (JMA) and numerical model outputs have been used to investigate line-shaped bands that caused heavy rainfall (e.g., the Shimane heavy rainfall event in July 1983, Kagoshima heavy rainfall event in August 1993, and Niigata heavy rainfall event in August 1998) (Watanabe and Ogura, 1987; Kato, 1998; Kato and Goda, 2001). Watanabe and Ogura (1987) noted that the linear convective band in the Shimane heavy rainfall event was generated along a convergence line that was induced by a mountain range. During the Kagoshima heavy rainfall

event, low-level, moist, warm air converged along the stationary Baiu front and generated several convective bands in the meso- β precipitation region. Cell tracks in these bands indicate that cells had back-building characteristics. Kato (1998) investigated the development mechanisms of the low-level jet, as well as the formation mechanisms of the bands and the characteristics of the cells.

Ishihara *et al.* (1995) and Kawashima *et al.* (1995) described a second type of precipitation band in the Baiu front; this band moved rapidly southward over northern Kyushu on 28 July 1988. The band did not cause flooding, but gusts of 16.1 m/s occurred as the band passed. Mid-level dry inflow that evaporated rain droplets helped intensify these gusts. Such mid-level inflow is frequently an important feature of squall lines observed in the U.S. and over tropical regions. They concluded that the band on 28 July 1988 was of the squall-line type. Squall-line type bands are not commonly observed in the Baiu front; further analysis of such bands in the Baiu front is warranted.

In addition to these case studies, other meso- β convective bands in the Baiu front have been analyzed (e.g., Seko *et al.*, 2000; Kato *et al.*, 2001). However, most analyses of heavy rainfall events focused on one type of convective band. In the present study, a few line-shaped bands and one hook-shaped band were observed in the same meso- β precipitation region. Numerical models simulated another type of meso- β line-shaped band. Structural comparisons between the different types of bands will provide insights to heighten the comprehensive understanding of band properties. Comparative analyses are performed using data from the Torrential Rain Experiment (TREX) and operational meteorological data from the JMA. In addition, output from the Meteorological Research Institute Non-Hydrostatic Model (NHM) (Saito and Kato, 1996) described the structure of the entire precipitation system including three types of the bands. The goal of this study is to show the structure of the bands and to diagnose the factors that determine band type.

Section 2 details the convective bands that were analyzed using observed data. The numerical model and the simulated results are described in Section 3. Comparisons between the convective bands are made in Section 4, and Section 5 presents the study conclusion.

2. Observations of the bands

2.1 Observations

TREX was an observational experiment that was designed to study mesoscale precipitation systems in the Baiu front from June to July 1996. It was undertaken by the Meteorological Research Institute (MRI), the

Fig. 1. Observation sites for the TREX experiment. Circles and squares indicate Doppler radar and sonde sites, respectively. The broken line is the location of the vertical cross section in Fig. 4. The shaded region indicates the precipitation region at 0830 JST.

Communications Research Institute, Tokyo University, Nagoya University, and Kyushu University (Sakakibara *et al.*, 1996). The experimental domain was southern Kyushu where the Baiu-front causes frequent floods and landslides during early summer. Supplemental observations were provided by Doppler radars at three sites on Yakushima and Tanegashima islands; by special upper air soundings at Tairajima, Ioujima, Minamitane, and Uchinoura; by JMA operational sites at Naze, Kagoshima, and Fukuoka; and by JMA meteorological observation vessels (Fig. 1). The present study mostly used upper air sounding data and Yakushima Doppler radar data.

2.2 Features of the meso- α precipitation system

The precipitation system that contained the meso- β precipitation bands passed through the TREX observation area on 7 July 1996. Figure 2 shows weather maps at 0900 Japan Standard Time (JST), which corresponds to 0000 UT, and includes features of the meso- α distributions in which the precipitation system was developing. The precipitation system was developing around a meso- α low-pressure system west of Kyushu, in a zone of low pressure between two areas of high pressure centered south of Okinawa and over Hokkaido (Fig. 2a). The Baiu front extended from China to the south coast of Japan, through this low-pressure

Fig. 2. Weather maps at 0900 JST 7 July 1996 at (a) 500 hPa, (b) 850 hPa, and (c) the surface. The shaded region in (b) indicates the humid region where $T-T_d < 4$ degree.

system. A humid zone at 850 hPa, which will henceforth be called a 'humid tongue,' extended along this surface Baiu front (Fig. 2b). Southwesterly flow prevailed between the area of high pressure to the south and the Baiu front, supplying moisture from the southern East China Sea to the Baiu front. A cyclonic circulation accompanied the low-pressure system near Kyushu, and thus northerly and southerly flows dominated on the western and eastern sides of the low-pressure system, respectively. A pressure trough was just over Kyushu, and intense westerly flow was observed over northern Kyushu at 500 hPa. Airflow on the western and eastern sides of Kyushu also had northerly and southerly wind components, respectively.

2.3 Features of the meso- β precipitation regions

Figure 3 shows cloud images observed by a geostationary meteorological satellite (GMS) on 7 July 1996. Clouds developed around the meso- α low-pressure system west of southern Kyushu (Fig. 3b). The precipitation system analyzed in this study developed within these clouds. The clouds began to develop at 2200 JST on 6 July and stayed near southern Kyushu for more than 17 hours. The precipitation system included four meso- β cloud regions: cloud region developed on the southern side of the Baiu front, and cloud regions developed in the Baiu front. Cloud region was near the low-pressure system; regions and were to its southwest. Cloud region was nearly stationary, whereas cloud regions moved eastward. Thus, cloud regions and merged with region at 1139 JST and 1238 JST, respectively, and individual cloud regions could not be identified after 1238 JST.

Figure 4 shows a vertical cross section of equivalent potential temperature (θ_e), relative humidity, and horizontal wind from upper air soundings, which intersect cloud regions and (Figs. 1 and 3). Humid air ($> 80\%$) extended upward to nearly 300 hPa inside the cloud region from Ioujima to Vessel-Choufu. This humid region matches the humid tongue shown in Fig. 2b. Southwesterly winds prevailed below 550 hPa to the south of the cloud region. High- θ_e air was supplied to the Baiu front below 900 hPa by the southwesterly inflow. This supply of high- θ_e air was able to maintain convection in cloud region. Dry air above the low-level inflow intruded into cloud region from the south, reaching Uchinoura and Kagoshima. The wind directions are consistent with flow expected from the weather maps: southerly winds prevailed on the southeastern side of the meso- α low-pressure system where cloud region developed. A second layer of dry air was on the north side of the cloud regions. At Vessel-Choufu, close to cloud region, northerly flow was observed at 600 hPa. Because northerly airflows from 750 hPa to 550 hPa are

Fig. 3. Infrared GMS images from 0733 JST to 1238 JST on 7 July 1996. Numbers ~ indicate the four meso- β precipitation regions comprising the precipitation system. Panel (b) is overlaid with the surface weather map at 0900 JST.

Fig. 4. Vertical cross section of horizontal wind (flags and barbs), equivalent potential temperature (solid and broken lines), and relative humidity exceeding 80% (shaded area) along the broken line in Fig. 1 at 0900 JST on 7 July 1996.

thought to have entered the humid zone from the northwest, the northerly airflow over Vessel-Choufu might be a part of this northerly airflow. Dry air at mid-levels can enhance convection, influencing the type and shape of the convective bands, when the dry air enters the precipitation region. Thus, the airflow structure in this precipitation system was investigated using a numerical model output and is described in Section 3.

The meso- β cloud regions seen in Fig. 3 were also identified as precipitation regions by radar echo patterns. Figure 5 shows that meso- β precipitation regions were composed of meso- γ convective cells surrounded by weaker precipitation regions. The boundaries of the meso- β precipitation regions in Fig. 5 were determined by GMS images and by the motion of the intense convective cells. For example, groups of intense precipitation cells moved eastward and southeastward in regions and , respectively.

Two types of convective band made of convective cells existed in precipitation region . Convective bands in the meso- β region suggest that there was a multi-scale structure within the meso- β precipitation regions. The scales of precipitation regions ~ and the scale of the convective bands are henceforth referred to as meso-

β_L and meso- β_S , respectively, in this study.

One type of meso- β_S convective bands was the line-shaped convective bands L that were generated side by side along the southern edge of the meso- β_L precipitation region. Convective bands of this type occurred when precipitation region was northwest of precipitation region (~1000 JST). The second band was a hook-shaped convective band H that evolved from the group of intense convective cells over the western part of region . Band H formed as cloud region passed through southeastern Kyushu (~1200 JST). The convective band type, which is characterized by shape and structure, is determined by environmental conditions surrounding the convective bands (e.g., the vertical profiles of horizontal wind and water vapor). Thus, the evolution of the band type from L to H suggests that region influenced the environment around region between 1000 JST and 1200 JST. The way in which the environment around region influences the meso- β_S bands is discussed in Section 3. Bands in precipitation region were observed by the Yakushima Doppler radar during TREX. The evolution of the convective cells and airflow structures of the bands in region were analyzed in detail using both Doppler and operational radar data.

Fig. 5. Precipitation intensity estimated by the JMA operational radar at Tanegashima from 0800 JST to 1500 JST, 7 July 1996. Symbols $\sim$ indicate the meso- β_1 precipitation regions. Meso- β_2 precipitation bands L and H in the region I are indicated by arrows. Boundaries of meso- β_1 precipitation regions $\sim$ were determined by comparison with the GMS images and by the motion of the precipitation regions.

2.4 Linear convective bands L

Figure 6 shows the precipitation intensity as observed at 7-min intervals by the operational radar at Tanegashima. Two line-shaped bands L extended northeastward from the southern edge of precipitation region. Region was almost stationary, but the bands L within it moved slowly eastward. New convective cells formed at the southwestern tip of each band (e.g., cells *iii*, *iv*, and *iii* at 1137 JST and cell *iv* at

1152 JST in Fig. 6) and then moved northeastward along the bands. This time evolution of cells indicates that the bands L were of the back-building type. The exception was the westernmost group of intense convective cells in Fig. 6, which evolved into the hook-shaped band H.

The bands L passed near the Yakushima Doppler radar at about 1030 JST, allowing horizontal wind distributions in the bands to be estimated using simplified volume velocity processing (VVP) methods

Fig. 6. Precipitation intensity from 1122 JST to 1200 JST from the Tanegashima operational radar. Convective cells in line-shaped bands are marked with Roman numerals.

Fig. 7. Yakushima Doppler radar observations of horizontal wind relative to band L and the reflectivity field in and around band L at 1026 JST, 7 July 1996. High reflectivity regions ($> 30\text{dBZ}$) in band L at a height of 1.0 km are enclosed by thick lines. Broken circles indicate convergence along the southwestern part of the band at 1.0 km and along the northeastern part of the band at 2.0 km.

(Tatehira and Suzuki, 1994; Tatehira *et al.*, 1995). A fan-shaped area, measuring 2 km in the radial direction and 8 degrees in the tangential direction, was adopted as the unit of estimation. Figure 7 shows the horizontal distributions of reflectivity and wind relative to the line-shaped band L at 1026 JST. Strong convective cells ($\geq 40\text{ dBZ}$) aligned in the convective band as shown in Fig. 6.

At heights of 1.0 km and 2.0 km, southwesterly flow dominated near band L. The wind direction near band L was consistent with the inflow below 550 hPa on the southern side of the precipitation system (see Fig. 4). Relatively strong flow from the south at a height of 1.0 km converged with weaker flow near the southwestern cells of the band. In the northern part of the band, the convergence was more remarkable at 2.0 km. Such distributions suggest that low-level convergence at the windward tip of the band generated the new cell and that convergence at 2.0 km was produced downwind of the band by the developing cells.

2.5 Hook-shaped convective band H

A hook-shaped convective band developed as precipitation region moved to southeastern Kyushu. Reflectivity fields in Figs. 5, 6 and 8 show that a group of intense convective cells in the western part of region started to deform at 1130 JST, evolving to a hook-shaped band H by 1200 JST. The developed cells in band H were more densely packed and had more intense precipitation than the bands in L (Fig. 8). The hook-shaped band H moved to the southeast and merged with small cells on the front side of the band (e.g., 1145 JST and 1222 JST in Fig. 8) as it moved.

Figure 9 shows the horizontal wind relative to the ground at 1207 JST. Strong northwesterly flow below 2.0 km entered band H from its rear (northwestern) side, producing intense convergence along the front (southeastern) side. The intense northwesterly flow converged with high- θ_e air transported from the south by low-level inflow (see Figs. 2 and 4). The lifting of the high- θ_e air may have generated the new cells at the front of the band. Such features, i.e., intense rear inflow and movement with the merging of new convective cells at the front of the band, are characteristic of squall lines.

3. Numerical simulation of the precipitation system

Detailed data for fields in the vicinity of the bands are required at scales larger than those observed to determine the airflow around bands L and H and the factors that determine the band type. When the environment of a meso- β precipitation region differs from the environment in region , a different type of precipitation band will form. Numerical simulations were performed to obtain detailed fields of the whole precipitation system.

3.1 Description of the numerical model

The precipitation system in this study was reproduced with a fully compressible version of the NHM (Saito and Kato, 1996). The horizontal grid was $200\text{ km} \times 200\text{ km}$ in the x and y directions with a

Fig. 8. Precipitation intensity from 1137 JST to 1237 JST from the Tanegashima operational radar. Arrows indicate small convective cells in front of band H merged by the hook-shaped band.

horizontal grid spacing of 5 km; the model domain covers the whole precipitation system. The horizontal grid resolution of 5 km supported the simulation of individual convective cells and airflow through the bands. There were 38 vertical layers. The top boundary was at 19.82 km. Layer depth increased with height, from 40 m to 1120 m for the bottom and top layers, respectively. The time step was 5 s. The mixing ratios of ice cloud, snow and graupel, cloud water, and rainwater content were all predicted explicitly. The initial and boundary conditions were produced from Regional Spectral Model (RSM) forecasts (JMA, 2002). The initial time of the RSM was

2100 JST 6 July 1996. Initial conditions of the NHM were produced by spatial interpolation of the 6-h RSM forecast. NHM boundary conditions were derived from RSM output at 3-h intervals using temporal and spatial interpolation.

3.2 Simulated meso- α features

Horizontal fields of surface pressure, θ_e , and horizontal wind at 0300 JST 7 July 1996, which were the fields used as initial conditions in the NHM simulation, are shown in Figs. 10b and 11. The position of the meso- α low and the distribution of surface pressure resemble

Fig. 9. Yakushima Doppler radar observations of horizontal wind relative to the ground and the reflectivity field in and around band H at 1207 JST, 7 July 1996. High reflectivity regions ($> 30\text{dBZ}$) in band H at 1.0 km are enclosed by thick lines.

the observations (Fig. 10a). Near the surface, southwesterly high- θ_e flow ($> 350\text{K}$) reached western Kyushu in the East China Sea and southern Shikoku, and formed a convergence zone with the northwesterly flow or weak flow from the north (Fig. 11a). This convergence zone is the surface Baiu front. At a height of 5.91 km, a high- θ_e region ($> 338\text{K}$), corresponding to the humid tongue in Figs. 2 and 4, extends from the East China Sea to south of Shikoku (Fig. 11b). The proximity of the high- θ_e region at 5.91 km and the surface Baiu front suggests that the low-level convergence of high- θ_e air produced the humid tongue. The simulated distributions of θ_e and horizontal wind are consistent with weather maps and distributions observed by upper soundings. As the meso- α comparisons showed that the simulated distributions were similar to observations, simulated fields were used for analyses.

3.3 Simulated features of the meso- β_1 precipitation regions

Figure 12 shows simulated precipitation amounts at intervals of 30 min, from 0600 JST (Forecast Time, FT = 3h00m) to 0930 JST (FT = 6h30m). A precipitation system developed over southern Kyushu, and then persisted for longer than 6 hours. The precipitation system was divided into three meso- β_1 precipitation regions, ~, according to the motion of the group of intense convective cells. Precipitation region extended in the east-west direction and stayed along southern Kyushu; precipitation region moved east-southeastward along the northern edge of region; and precipitation region moved to the east and then merged with region at 0930 JST (FT = 6h30m). The simulated evolutions of meso- β_1 precipitation regions were similar to the GMS observations (see Fig. 3),

Fig. 10. (a) Weather map at 0300 JST, 7 July 1996. (b) Surface pressure at 0300 JST simulated by the Regional Spectral Model of the Japan Meteorological Agency.

Fig. 11. Horizontal wind (arrows) and equivalent potential temperature (contour lines) at 0300 JST at (a) 20 m and (b) 5.91 km. Thick lines in (a) and (b) indicate the 350 K and 338 K contours, respectively.

Fig. 12. Thirty-minute precipitation regions produced by NHM. Precipitation areas are divided into meso- β precipitation regions ~ by the broken lines.

although the generation time of the precipitation system was shifted to 3.5 hour earlier, and precipitation region was not generated.

3.4 Simulated features of the meso- β s precipitation bands

Figure 13 shows the precipitation intensity at 0630 JST (FT = 3h30m) and 0800 JST (FT = 5h00m). Each meso- β _L region was composed of intense convective cells and adjacent regions of weaker precipitation. When the meso- β _L precipitation region was over western Kyushu, several line-shaped convective bands L, which were composed of intense convective cells, formed in region (Fig. 13a). A hook-shaped band H that expanded to the southeast also formed when region was over Kyushu (Fig. 13b). The relationship between the position of region and the shapes of meso- β s bands in region is similar to the observations (see Fig. 5). A more detailed evolution of the convective cells in the bands L and H will be discussed in the following subsections.

(1) Convective cell evolution in the meso- β s scale bands

Figure 14 shows precipitation intensity around bands L from 0615 JST (FT = 3h15m) to 0655 JST (FT =

Fig. 13. Simulated precipitation intensity at 0630 JST, 7 July 1996 (Forecast Time = 3h30m) and 0800 JST (FT = 5h00m). Meso- β _L precipitation regions ~ are enclosed by broken lines. Bands L and H are outlined in thick lines.

3h55m). Two line-shaped bands extended from southwest to northeast. New convective cells in the bands formed at the southwestern tip (e.g., cell *iv* at 0635 JST and cell *v* at 0645 JST in Fig. 14) and then moved northeastward inside the bands. The cells in bands L had characteristics of back-building cells.

Figure 15 shows the precipitation intensity from 0745 JST (FT = 4h45m) to 0805 JST (FT = 5h05m). A

Fig. 14. Simulated precipitation intensity from 0615 JST to 0655 JST, 7 July 1996. Thick lines at 0635 JST are the outlines of two precipitation bands L. Convective cells in line-shaped bands are marked with Roman numerals.

Fig. 15. Simulated precipitation intensity from 0745 JST (FT = 4h45m) to 0805 JST (FT = 5h05m), 7 July 1996. The thick line and arrows indicate hook-shaped precipitation band H at 0800 JST and its movement, respectively.

hook-shaped band H that evolved from the westernmost band in region expanded to the southeast. Convective cells were more densely packed in H than in bands L, and the width of the precipitation area exceeded that in bands L. The shape of the band and the direction toward which band H expanded were both similar to observations. Although the new convective cells observed at the front of the band H were not reproduced,

NHM reproduced most of the characteristics of the observed bands. Thus, the environment of the meso- β s bands, i.e., the meso- β _L scale distribution of horizontal wind and θ_e , was investigated.

(2) Meso- β _L features of horizontal wind and θ_e around the meso- β _s bands

Figure 16 shows the horizontal distributions of θ_e and horizontal wind at 0630 JST. Low-level inflow from the south transferred high- θ_e air ($> 355\text{K}$) to the precipitation system, where it converged with low- θ_e airflow under regions and along the line CL1 in Fig. 16a. The convergence suggests that precipitation regions and were sustained by the supply of high- θ_e air from the south. The precipitation region was generated along line CL2, where northwesterly flow of relatively high- θ_e (350–355 K) converged with the flow in the system. Even though the θ_e of this air was lower than the θ_e of the low-level inflow coming from south of the system, precipitation region was sustained by this relatively high- θ_e air.

Figure 16b shows horizontal fields of wind and θ_e at a height of 2.1 km. A southwesterly flow of low- θ_e air that had moved from roughly the same direction as the low-level inflow dominated in region where line-shaped bands L occurred. This unidirectional flow environment in region is common to the observed wind fields and is important for line-shaped meso- β s bands. In regions and , westerly flow of high- θ_e ($> 340\text{K}$) air prevailed. Because the wind direction of the mid-level flow differed from that of the low-level inflow, different band types were generated in these regions. The convective bands simulated in region will be discussed in Section 4.

Figure 17a shows the θ_e and horizontal wind fields near the surface when band H was mature. A comparison with the airflow near bands L at 0630 JST suggests that the most notable difference is the speed of the westerly or northwesterly airflow under the meso- β s bands. The westerly or northwesterly airflow under band H was stronger. Namely, the rear inflow for band H exceeded 12 m/s, whereas the wind velocity under bands L was about 8 m/s. This more intense northwesterly flow was consistent with the intense rear inflow observed by Doppler radar (Fig. 9). The low-level inflow of high- θ_e air from south of the system, which then converged with intense northwesterly flow, was similar to that at 0630 JST. At 2.1 km (Fig. 17b), the precipitation system was between low- θ_e ($< 340\text{K}$) regions and the low- θ_e region northwest of precipitation region did not reach the hook-shaped band H. This distribution of low- θ_e air suggests that the northern low- θ_e air did not enter band H.

Fig. 16. Simulated equivalent potential temperature and horizontal wind fields at 0630 JST, 7 July 1996, at heights of (a) 20 m and (b) 2.1 km. Solid and thin dotted lines indicate precipitation rates exceeding 1 mm/h and coastlines, respectively. Thick broken lines divide the precipitation system into meso- β_1 precipitation regions. Thick dotted lines in panel (a) are low-level convergence. Solid and broken circles indicate the line-shaped bands L and the northwesterly or westerly wind region from the convective band in the region.

Fig. 17. As in Fig. 16 but for 0800 JST (FT = 5h00m). Broken-line circle in (a) denotes the northwesterly or westerly wind region under convective band H.

3.4 Trajectory analysis

The previous subsection noted a difference in intensity between the low-level rear inflow for bands L and the hook-shaped band H. Although band H had intense rear inflow, which was common to the squall lines, the origin of the low-level rear inflow has not been clarified. If the low- θ_e air northwest of precipitation region entered the hook-shaped band H, then band H had a structure similar to that of a squall line. Trajectories of tracer particles moving at the speed of the air were analyzed to show more clearly the structure of airflow in the bands.

(a) Trajectory analysis on the meso- β_s bands.

Tracer particles were placed around convective bands L at 0630 JST (FT = 3h30m) and were then followed for 2 hours backward and forward in time. Figure 18a schematically illustrates the airflow structure near the line-shaped bands L.

Low-level inflow entered bands L from the south, ascended to a height of 3 km or more, and flowed out to the northeast. Tracers that started above 2.0 km before 0630 JST (FT = 3h30m) passed between the meso- β_s bands. Airflow that converged with the low-level inflow from the south was traced back in time. That air had originated at a height of 1.0 km on the southern side of the system. Some air that was initially at 1.0 km changed its direction of motion from northeast to southeast, owing to the pressure gradient force (not shown), and then converged with the low-level inflow under the bands L.

The airflow structure around the hook-shaped band H is shown in Fig. 18b. Air that started below a height of 1.0 km entered the southeastern flank of band H and ascended rapidly to above 3 km. The airflow from 2 km passed around the northern or southeastern side of band H, and then descended more than 500 m during the tracing period. Intense rear inflow under band H originated in a southwesterly flow from a height of 1.0 km on the western side of band H. This southwesterly flow passed through decaying meso- β_L region . While passing region , the southwesterly flow changed to low-level intense northwesterly flow. Because this intense northwesterly flow region coincided with the low- θ_e region that emerged from the meso- β_L region (Fig. 17a), the intense low-level rear inflow of band H was the cold outflow that evolved from the southwesterly flow under the influence of the decaying convection in region .

(b) Difference between the line-shaped bands L and the hook-shaped band H

Comparisons between the airflow structures of bands H and L reveal similarities. Both bands had low-

level inflows from the south, mid-level flows that passed by the bands, and rear inflows that entered the bands from the northwest. Although low-level rear inflow converged along the front side of band H was more intense, the airflow structure of band H was similar to that of bands L.

The intensity of the rear inflow influenced the shape of the bands. In the hook-shaped band H, an intense rear inflow strengthened the convergence along the southeastern flank of the band and helped develop the hook-shaped updraft. In contrast, the line-shaped bands L were characterized by weaker convergence along the flank because of weaker rear inflow, and relatively stronger convergence occurred mainly at the southern tips of the line-shaped bands L. Line-shaped bands were produced by cells that were generated on the southern tips of the band. The cells were then moved downwind by mid-level flow. Thus, the shapes of the meso- β_s bands L and H can be related to the intensity of the rear inflow.

4. Convective bands in other precipitation regions and other case studies

Sections 2 and 3 have analyzed the characteristics of meso- β_s line-shaped bands L and hook-shaped bands H in precipitation region . In this section, comparisons between convective bands in precipitation region and other case studies yield common characteristics of the bands and factors that determine the band type.

Precipitation region west of southern Kyushu was not observed by TREX. Therefore, simulation results were used instead of observations. A convective band that developed parallel to a low-level convergence at 0630 JST and 0800 JST characterized region (Figs. 16 and 17). Low-level inflow that supplied high- θ_e air from south of the precipitation system was common to regions and , but the mid-level wind direction in region differed from that in region . Westerly flow, which was parallel to the low-level convergence, dominated in region . Figure 19 shows the evolution of the convective cells in the bands. Cells that were generated at the windward tip of the band (e.g., cell iv at 0605 JST) were moved downwind by the mid-level airflow. The cells also developed while they moved downwind, even if they were not at the windward tip of the band (e.g., cell ii). Low-level inflow supplied high- θ_e air along the entire flank of the meso- β_L convective band and then convective cells in contact with the low-level inflow were maintained. Therefore the horizontal scales of the band and the low-level convergence in region were similar. The band in region had different characteristics from those of the line-shaped bands L and hook-shaped bands H.

Kato (1998) investigated in detail a precipitation

Fig. 18. Illustrations of (a) line-shaped bands and (b) hook-shaped band.

Fig. 19. Simulated precipitation intensity from 0600 JST (FT = 3h00m) to 0615 JST (FT = 3h15m) in precipitation region on 7 July 1996. Convective cells in line-shaped bands are marked with Roman numerals.

system that produced flooding rainfall over Kagoshima. In that heavy rainfall case, several line-shaped bands were organized in a meso- β precipitation region that extended from northwest to southeast over Kyushu. The evolution of cells in the bands was investigated using reflectivity fields from operational radar. New cells formed at the upwind tips of the bands and developed while moving downwind (Fig. 3.13 in Kato, 1998). Such evolution is consistent with back-building convective cells.

The heavy rainfall bands in Kato (1998) were well simulated by NHM, so the environment surrounding the bands is also expected to be reproduced. Simulated mid-level flow and low-level inflow near the bands were both westerly. Such unidirectional flow was also a feature of precipitation region in this case study. This characteristic common to both bands indicates that mid-level flow that enters a band from the same direction as low-level wind is one factor for forming the meso- β s line-shaped bands.

The hook-shaped precipitation band H was then compared with the squall-line type band observed over Kyushu in 1988. In both bands, the low-level convergence region along which the bands formed jutted toward the direction of movement. Convective cells in both bands were spatially continuous. However, the rear inflow that penetrated the squall line over Kyushu originated in mid-level dry air north of the squall line (e.g., Fig. 20 in Ishihara *et al.*, 1995), whereas the rear inflow near band H originated in the airflow south of the precipitation system. The low-level, rear inflow of band H was not produced by the evaporation of water in the band itself, but by another precipitation region. Because the mechanism forcing the rear inflow in the hook-shaped band H differed from that in squall lines, the hook-shaped band H was not a squall line type band.

5. Summary

Meso- β bands in a precipitation system over southern Kyushu on 7 July 1996 were analyzed, revealing the environmental factors that determine the band type. In meso- β of precipitation region, several meso- β s, back-building bands were organized in a unidirectional flow environment. Southwesterly low-level inflow generated the convective cells at the southern edge of region. Subsequently, southwesterly mid-level flow formed the line-shaped bands by moving the convective cells to the northeast. When cold outflow from the adjacent precipitation region reached region, the outflow bent the convergence region and a hook-shaped band was organized. The airflow structure of the hook-shaped band was similar to that of line-shaped bands. Therefore, the hook-shaped band was of the back-

building band type and not the squall line band type.

The meso- β_L band was simulated in precipitation region where mid-level flow was nearly perpendicular to low-level inflow. Mid-level airflow moved the convective cells downwind along the bands. Low-level inflow entered from the flank of the band while the cells moved downwind. As the low-level inflow that maintained the convection entered along the entire length of the band, the horizontal scale of the low-level convergence determined the band length.

The characteristic of new cell development at the windward tip of the meso- β_L band, as in the meso- β_S line-shaped band in region , is common. However, the environments and scales of the bands vary considerably. The mid-level wind direction is roughly perpendicular to the low-level inflow for meso- β_L bands, whereas it is parallel for meso- β_S bands. One meso- β_L band develops along the low-level convergence in a meso- β_L ; several meso- β_S bands extend from the low-level convergence in a meso- β_L region. Thus, meso- β_L bands and meso- β_S bands should be distinguished as different band types.

Comparisons of airflow structures and shapes of different meso- β bands revealed that the mid-level wind direction is one factor determining band type. Cold outflow that changes the shape of the convergence region also influences band shape. In the present case study, bands were analyzed in which the mid-level wind direction was the same or perpendicular to the low-level inflow. Bands in which the mid-level wind direction was counter to the low-level inflow were not analyzed here. A numerical experiment using simplified environmental conditions should be performed to confirm that these factors determine the type and shape of meso- β bands.

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1996年7月7日に南九州で観測されたメソ スケール降水帯の解析的数値的研究

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要旨

1996年7月7日に南九州上で発達した降水系内の3タイプのメソ スケールの降水帯を、数値モデルの出力や気象庁と九州豪雨観測実験の観測データを用いて解析した。

降水系は4つのメソ スケールの降水域から構成されていた。降水域Ⅱでは、一方向から風が吹く環境で、その中でいくつかの短い対流性降水帯が組織化した。これらの短い降水帯の対流は、バックビルディング型の特徴を持っていた。別の降水領域からの強い流出流が侵入した領域Ⅰの西部分では、鉤状の降水帯が発達した。別タイプのメソ スケールの降水帯が、降水域Ⅲ内に再現された。この降水帯では、中層風によって対流セルが風下に移動するときに、高相当温位の気塊が降水帯の側面から供給され、降水帯全体の対流が維持していた。

気流構造と降水帯の形状の比較から、中層の風向がメソ スケールの降水帯の型を決定する重要な役割を果たすことが示唆された。さらに、他のメソ スケール降水域からの冷たい気流が、降水帯の形状に影響を及ぼしていた。