

An observational study on baiu-frontal-meso-scale convective systems in the leeward side of small island

Y. Umemoto¹, M. Teshiba¹, Y. Shibagaki², H. Hashiguchi¹, M. D. Yamanaka³, S. Fukao¹, and X-BAIU-99 and -02 observation groups

¹Research Institute for Sustainable Humanosphere, Kyoto University, Uji, Kyoto 611-0011, Japan

²Osaka Electro-Communication University, Neyagawa, Osaka 572–8530, Japan

³Graduate School of Science and Technology, Kobe University, Kobe 657–8501, and Institute of Observational Research for Global Change, Yokohama 236-0001, Japan

Abstract. On 28–29 June 1999 and 1 July 2002 during the observation period of the X-BAIU-99 and -02, orographic rainbands, the Koshikijima line, extending north-eastward from the Koshikijima Islands were observed by C-band weather radars, wind profilers rawinsondes and other instruments. The Koshikijima line observed in 1999 was maintained for 11 h. It was well developed especially until 03:00 JST and was about 200 km in length and 20 km in width for 4 hours from the beginning. The Koshikijima line observed in 2002 repeated generation and decay for 11 h, and not developed relatively. Around the Koshikijima line in each case, convectively unstable stratification with large Froude number, large CAPE, and low LCL was found. It is reasonable that upslope airflow in this layer can trigger convections forming the Koshikijima line. The horizontal wind in each case was very strong and southwesterly wind was dominant from the surface up to 5 km altitude. The wind direction changed clockwise below 3 km altitude. The wind observed in 1999 was much stronger than that of 2002. We consider that the horizontal wind component parallel to the rainband blew convective cells, and the perpendicular component played the role of supplying water vapor to the rainband.

1 Introduction

The summer monsoon rainfalls are identified as Meiyu in China and Baiu in Japan. A rainfall zone called the Baiu frontal zone stretches from the south of China to the Japan Islands during the Baiu season (June–July). In western Japan, the Baiu frontal zone is characterized by the existence of a low-level jet stream, weak temperature gradient, strong moisture gradient and nearly saturated neutral stratification (e.g. Matsumoto et al., 1970; Akiyama, 1975; Yoshizumi, 1977; Ninomiya, 1984, 1989, 2000, 2001).

Correspondence to: Y. Umemoto
(umemoto@rsh.kyoto-u.ac.jp)

Heavy rainfall frequently occurs over a region from the East China Sea to Kyushu, Japan, in the warm-moist air flowing from the Pacific subtropical anticyclone to the Baiu frontal zone. The most striking feature of rainfalls in Kyushu is the line-shaped orographic rainfall which appear to the south of the Baiu front and lasts for a long time. Yoshizaki et al. (2000) examined both a wide and a narrow rainband, which appeared stationary and was maintained for a long time over Kyushu, by using a non-hydrostatic spectrum model of MRI/NPD-NHM developed by the Japan Meteorological Agency (JMA). The generating and maintaining mechanisms of the wide rainband were clarified. On the other hand, the narrow rainband was not simulated because the resolutions of the models are not fine enough. To investigate the mechanisms of such rainfall systems, it is necessary first to perform intense observations.

In this study, wind profilers (WPs) were operated together with C-band weather radars, rawinsondes and other instruments, in a special observation campaign called “X-BAIU” which was conducted over the East China Sea and Kyushu during the Baiu seasons from 1998 to 2002 (Kato et al., 2003). During the special observations, narrow rainbands (referred to as “the Koshikijima line”) extending northeastward from the downdraft area of the Koshikijima Islands (see Fig. 1) were observed during the period on 28–29 June 1999 and 1 July 2002. The main purpose of this paper is to show how combined WP-weather radar observations are an important tool for studies to reveal the mechanism of orographically-affected narrow rainbands such as the Koshikijima line.

2 Observation data

The observation sites of the field observations “X-BAIU-99” and “X-BAIU-02” around the Koshikijima line are shown in Fig. 1. The Koshikijima Islands are located to the west of Kyushu where the oceanic air flows in directly. It has small low mountains, ranging in the southwest-northeast direction.

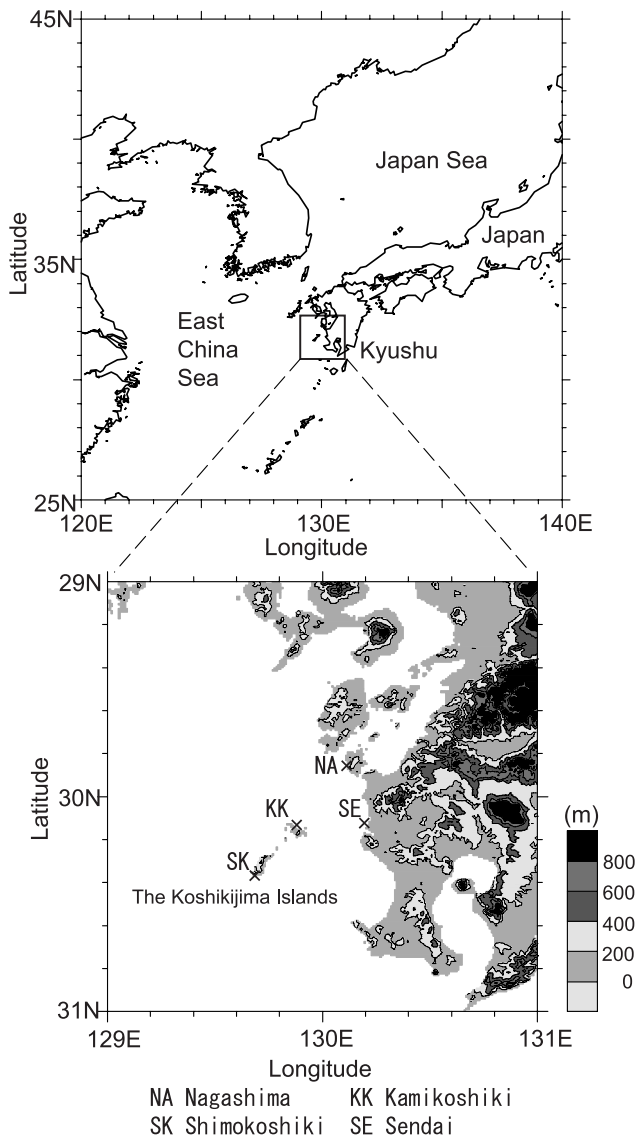


Fig. 1. Topographic map of observation sites

The mountains are 500–600 m in height, much lower than the central mountains of Kyushu. Nagashima (32.1°N , 130.1°E), referred to as “NA” in this paper, is located on the leeward side of the Koshikijima line, about 50 km northeast of Kamikoshiki (31.9°N , 129.9°E), referred to as “KK”, and its altitude is about 400 m. Sendai (31.9°N , 130.2°E), referred to as “SE”, is located about 40 km east of KK. Upper air soundings were made at Shimokoshiki (31.6°N , 129.7°E), referred to as “SK” and NA during the observation period in 1999 and also made at NA in 2002.

An S-band (3 GHz frequency) WP was installed at NA and KK during the observation periods in 1999 and 2002, respectively. L-band (1.3 GHz frequency) WPs were installed at NA and SE during the period in 2002. In 2002, three WPs were installed and observed wind behaviors at the generating point (KK), downwind side (NA) and surrounding area (SE) of the Koshikijima line. WP observations are well suited to

examine detailed wind behavior including the vertical wind component associated with mesoscale cloud systems. WPs can observe clear-air motion which cannot be observed by weather radars. Wind behavior just before and/or after a precipitation event can also be observed.

The characteristics of precipitating clouds were observed by the operational C-band weather radars operated by JMA. The operational radars obtained the horizontal distributions of rainbands widely. The rainband extending northeastward from the Koshikijima Islands was observed from 23:00 JST (JST = UTC + 9) on 28 June to 10:00 JST on 29 June 1999, and from 03:00 to 14:00 JST on 1 July 2002. As shown in Figs. 2 and 3, the Koshikijima line is a narrow rainband extended to the leeward side of the background wind. The precipitation area corresponding to the Baiu front was also observed on the north of Kyushu.

In this study, we identified three periods, A, B, and C, based on the width and length of the rainband. The period from 23:00 JST on 28 June to 03:00 JST on 29 June 1999, were classified as period A, from 03:00 to 10:00 JST on 29 June 1999 as period B and from 03:00 to 14:00 JST on 1 July 2002 as period C. We define the three cases: for period A, the rainband was most developed; for period B, the rainband was less strongly developed, for period C, the rainband was developed weakly. In addition to these three periods, period D, from 14:00 to 16:00 JST on 1 July 2002, after the Koshikijima line had decayed, is shown for comparison.

3 Results

3.1 Synoptic condition around the Koshikijima line

In 1999, the Koshikijima line was aligned in the northeastward direction (about 35° from North), and was observed around 23:00 JST on 29 June. The wide (~ 20 km), long (~ 200 km) and strong (more than 32 mm/hour) precipitation echoes were observed. The Koshikijima line was well developed until 03:00 JST on 29 June (period A). After 03:00 JST, the width of echoes narrowed (~ 10 km), and the rainband merged into the Baiu front going southward around 10:00 JST (period B). The Koshikijima line was not so developed. Though the Baiu front went southward gradually, the Koshikijima line stagnated without changing its position for about 11 h. In 2002, the Koshikijima line was observed aligned in the northeastward direction (about 40° from North) from 03:00 to 14:00 JST on 1 July 2002 (period C). Since the width and length of precipitation intensity were smaller (~ 8 and ~ 120 km) than those observed in 1999, it was not so developed compared to the rainband observed in periods A and B. A rainband corresponding to the Baiu front was also observed in the north of Kyushu for this case. Though the rainband gradually went southward, the Koshikijima line stagnated without changing its position, as in 1999.

The surface weather chart at 09:00 JST on 29 June 1999 is shown in Fig. 4. The Baiu front extending east-westward was

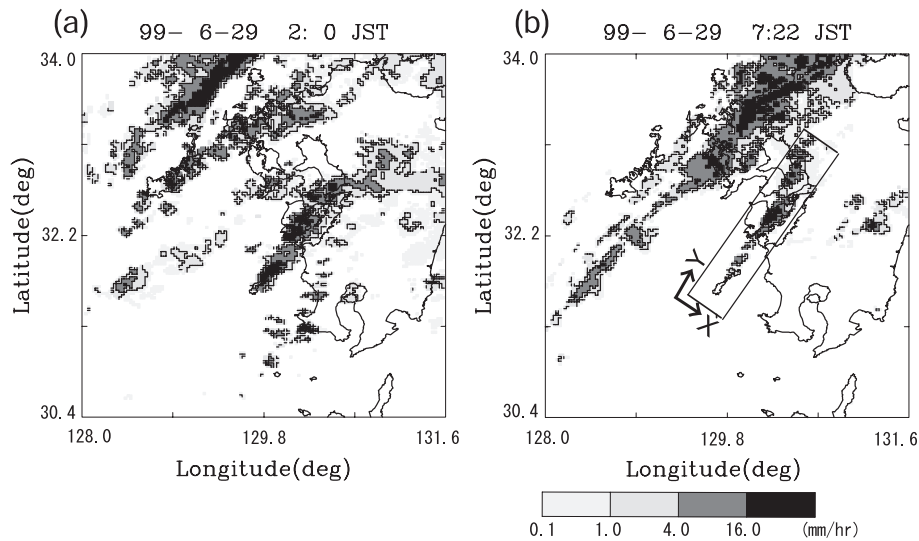


Fig. 2. Horizontal distributions of precipitation echo intensity at 2 km height observed by JMA operational radars at (a) 02:00 and (b) 07:22 JST on 29 June 1999 when orographic rainband denoted as the Koshikijima line was seen.

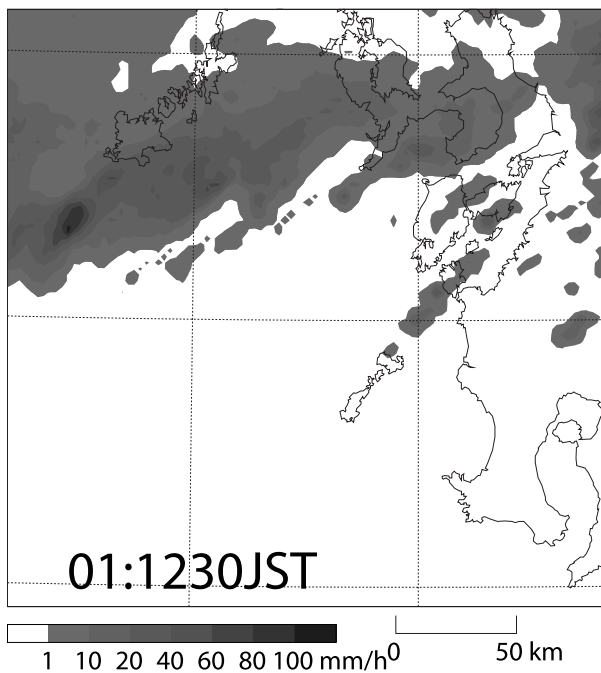


Fig. 3. The same as Fig. 2 but at 12:30 JST on 1 July 2002.

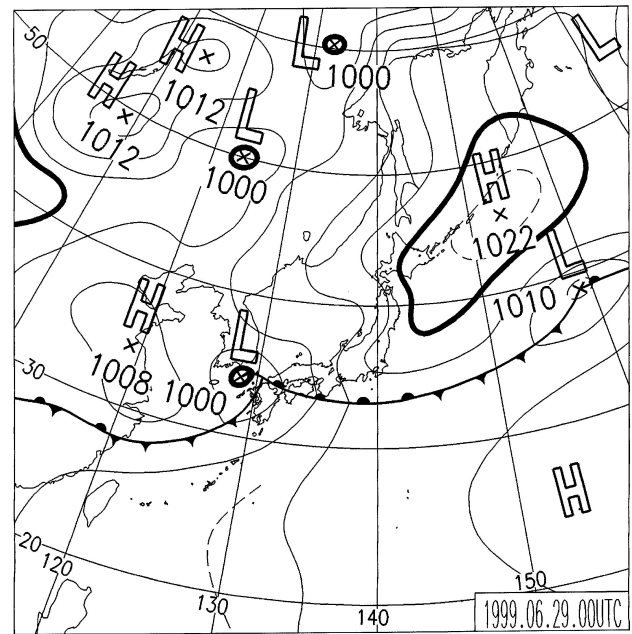


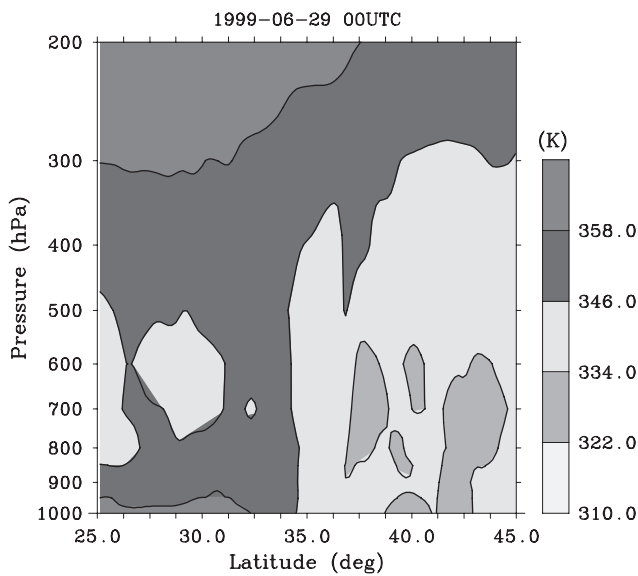
Fig. 4. Surface weather chart at 09:00 JST on 29 June 1999.

seen. Along 130° E, it was located to the north of Kyushu. The southern part of Kyushu was located in the warm sector of a low. Figure 5 shows the North-south vertical cross sections of equivalent potential temperature θ_e along 130° E using Regional objective ANALysis (RANAL) data produced by JMA at 09:00 JST on 29 June 1999. The atmosphere was convectively unstable in the south of the Baiu frontal zone (from 32° – 35° N), and stable in the north of the Baiu frontal zone. High θ_e was restricted below the 850 hPa level and

south of 32° N. Since the areas of high humidity was also restricted to the same region, the potential temperature depended on the amount of stream. The Koshikijima Islands are located around 30° N, and convectively unstable and moist atmosphere existed in the area at lower altitude below 850 hPa level. These synoptic overviews around Kyushu did not change much when the Koshikijima line was observed. These features were also seen in the case of 2002.

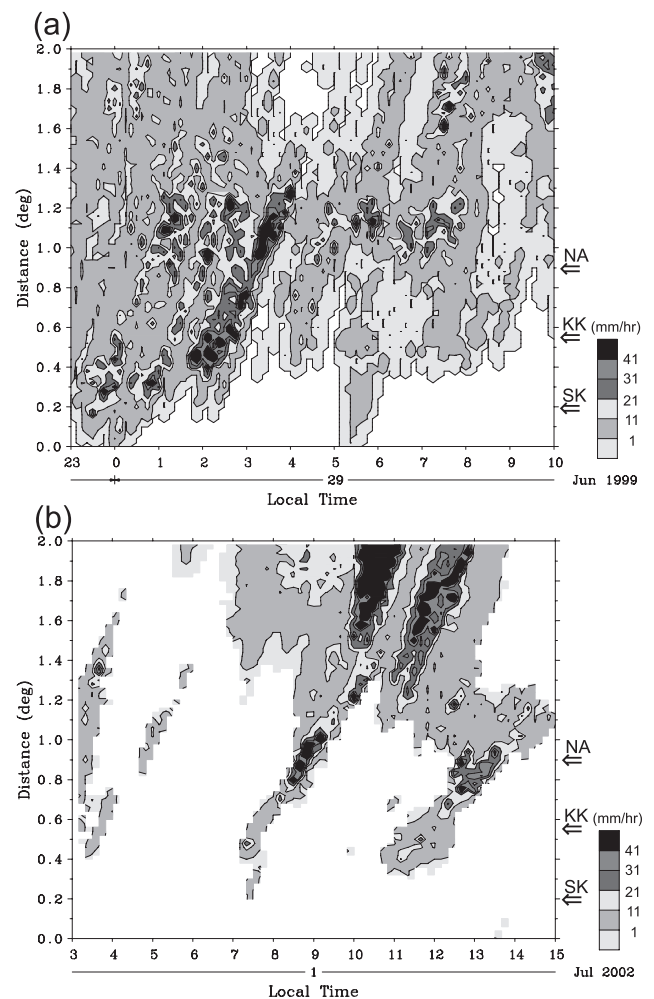
Table 1. Atmospheric parameters in for each observation location.

Period	Location	Date	LCL(m)	CAPE	Fr	q(g/Kg)	RH(%)
Before A	SK	1999/6/28/22:30	889	1031.3	1.8	16.6	95
A	NA	1999/6/28/23:30	1008	377.3	2.6	15.2	83
A	NA	1999/6/29/2:30	342	1596.2	2.1	16.6	95
B	SK	1999/6/29/4:30	374	1910.2	2.5	17.3	95
B	SK	1999/6/29/7:30	642	2057.2	1.3	18.4	97
Before C	NA	2002/6/30/20:30	136	346.8	0.5	13.2	71
C	NA	2002/7/1/2:30	237	1635.6	1.3	15.8	88
C	NA	2002/7/1/8:30	314	1835.6	1.4	15.9	89
C	NA	2002/7/1/2:30	171	2531.7	1.1	14.9	81

**Fig. 5.** North-south vertical cross section of equivalent potential temperature along 130° E.

3.2 Background field generating the Koshikijima line

Figure 6 indicates time series of the maximum rainfall intensity observed by JMA operational radars along the X-axis of the rectangle shown in Fig. 2b of which X- and Y-axis corresponded to the direction of from southeast to northwest and from southwest to northeast, respectively. In period A strong and stationary rainfall was observed and precipitating clouds were generated in the region between 0.0° and 0.4°, which corresponds to the southwest of the Koshikijima Islands, and moved northeastward one after another. On the other hand, precipitating clouds were generated over the Koshikijima Islands and precipitating intensity was comparatively weak in periods B and C. We consider that the rainband was generated through condensation and developed more rapidly in period A compared to that of the other periods. The stationary rainband which also developed around NA and moved northeastward was observed in periods A and B, while the rainband observed in period C was not maintained for a long time

**Fig. 6.** Time series of the maximum rainfall intensity of an X-axis in rectangle as shown in Fig. 2b observed by JMA operational radars on (a) 28–29 June 1999 and (b) 1 July 2002. Positions of NA, KK, and SK are indicated by arrows. See corrected section in paper.

and was weakened around the northeast of NA. The length of the rainbands observed in 1999 and 2002 was about 200 km and 120 km, respectively. We consider that the difference in the length of rainbands depends on whether rainband is able to develop around NA or not.

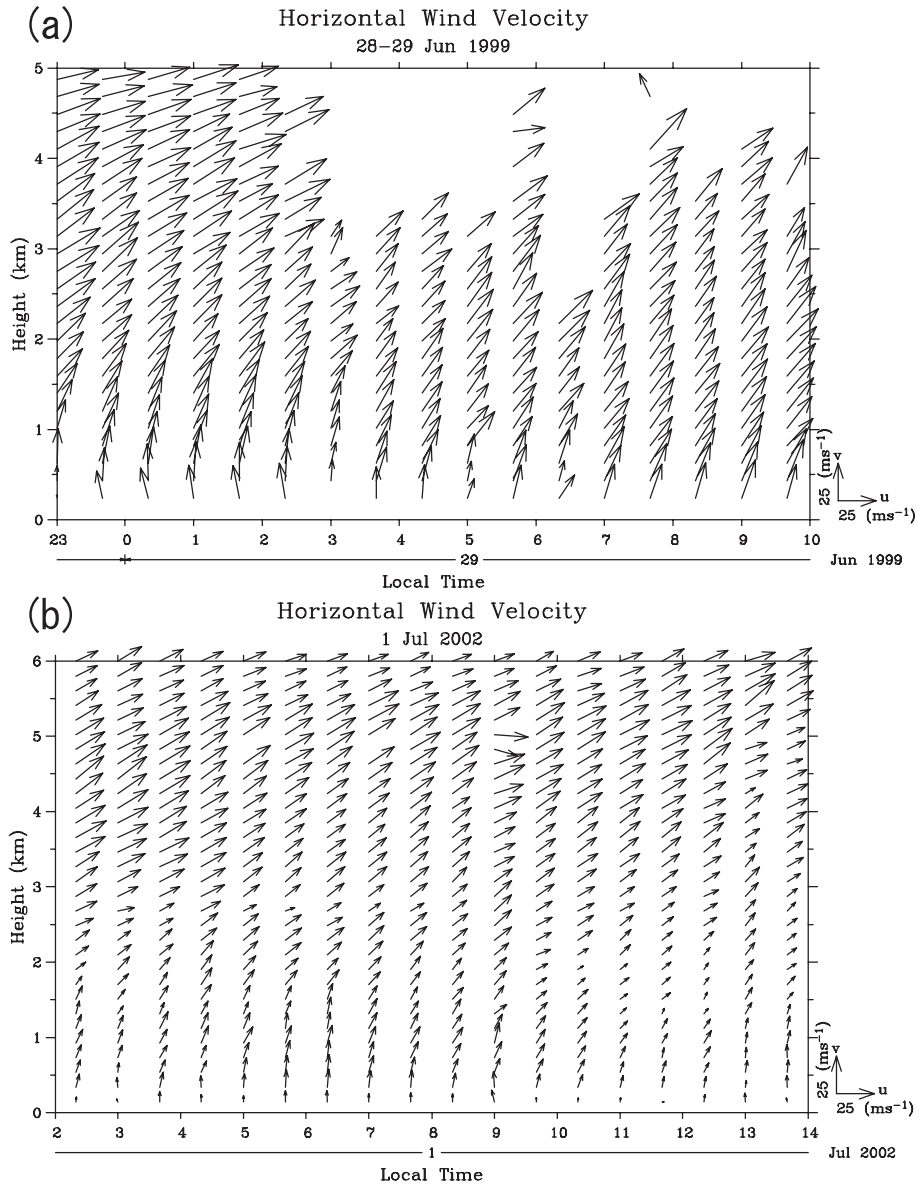


Fig. 7. Time-height cross-sections of horizontal wind observed by WP at (a) NA on 28–29 July 1999 and (b) NA on 1 July 2002.

Parameters calculated using rawinsondes launched at SK and NA are shown in Table 1. We calculated the Froude number $Fr = U/Nh$, where U is horizontal wind speed averaged below 600 m altitude, h is the height of the mountains of the Koshikijima Islands (600 m), and N is the Brunt-Väisälä frequency. Specific humidity (q) and relative humidity (RH) are averaged between sea level and 600 m altitude. While the Koshikijima line was observed (through periods A, B and C), Lifting Condensation Level (LCL) was below 400 m, which is below the tops of the mountains in the Koshikijima Islands except for the data at 23:30 JST on 28 and 07:30 JST on 29 June 1999 when CAPE (Convective Available Potential Energy) index was large enough to develop precipitating clouds. Following Smolarkiewicz and Rotunno (1989, 1990), the airflow with large Fr (> 1) among the present cases should rise over the mountains. Throughout periods A, B and C very

moist air in which q was more than 15 g/kg existed below 600 m altitude and the layer below 3 km altitude was convectively unstable around the Koshikijima line.

The structure of the narrow rainband was generated and maintained for a long time by the following process. Convective cells were generated continuously because of the orographic features of the Koshikijima Islands. The cells were advected to leeward by the lower wind one after another and then formed the rainband. While the Koshikijima line was observed, LCLs were lower than the tops of the mountains in the Koshikijima Islands and there was convectively unstable and very moist air in the lower layer of the atmosphere (below 850 hPa level). In addition, the value of the CAPE index was large enough to generate precipitating clouds. Therefore, if there was airflow ascending to the peaks of the Koshikijima Islands, a necessary condition for the generation of clouds

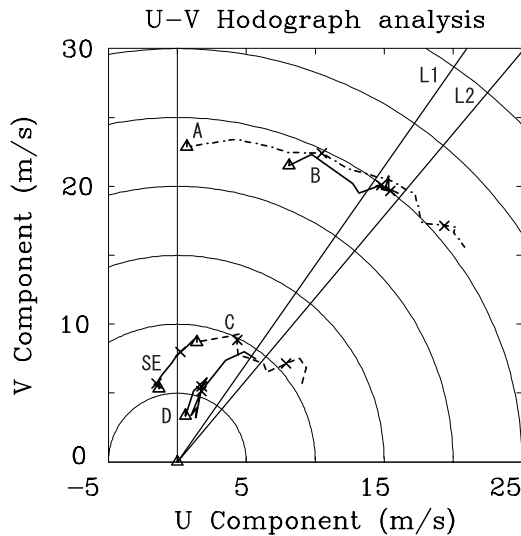


Fig. 8. Hodographs of horizontal wind at NA in periods A, B, C and D (when the Koshikijima line was not observed) and at SE in the period C. The lines L1 and L2 indicate the direction parallel to the rainband in 1999 and 2002, respectively. Triangles (Δ) indicate surface, and crosses (\times) are put on the curve at 1 km height intervals.

was satisfied, namely the upslope triggering for the convection, one of the seven mechanisms of orographic precipitation classified by Houze (1993).

3.3 Wind behavior along the Koshikijima line

Figure 7 shows horizontal wind observed by BLRs installed around the Koshikijima line. From 2300 JST on 28 June to 10:00 JST on 29 June (Fig. 7a), while the Koshikijima line was observed, the horizontal wind was very strong (more than 25 m/s) and southwesterly wind was dominant from the surface up to 5 km altitude. The wind direction changed clockwise below 3 km altitude. Yoshizaki et al. (2000) also found a similar clockwise rotation of wind direction with height for the rainband appeared over Kyushu, on 26 June 1998. On the other hand, wind direction was almost constant from 3 to 5 km.

In 2002, while the Koshikijima line was observed, southwesterly wind was dominant and wind speed increased with height, and the upward clockwise rotation of wind direction was also observed at NA (Fig. 7b). Wind speed was smaller than that observed in 1999, while its direction was almost consistent with that in 1999 below 3 km altitude. Wind behavior observed at KK was almost similar to that of NA.

Barnes and Sickman (1984), Alexander and Young (1992) and LeMone et al. (1998) examined the role of background wind shear in determining the structure of rainbands over tropical oceans. They concluded that nearly all rainbands occurring in winds with appreciable shear below a low-level wind maximum are oriented nearly normal to the direction of low-level shear (fast-moving squall line), while rainbands where the low-level shear is weak are oriented along the direction of the middle-level shear (slow-moving rainband).

The Koshikijima line had strong low-level shear below 3 km altitude, but it was a stationary band. Thus the classification rules are not apply to the Koshikijima line. Compared with the data observed at KK and NA, both wind speed and upward clockwise rotation of horizontal wind were weak at SE.

Figure 10 shows hodographs of horizontal wind observed by WP at NA and SE. Through periods A, B and C a wind component parallel to the rainband was observed below 3 km altitude. The component became weak when the Koshikijima line decayed, as in period D. That component of wind was especially strong in period A compared with B and C. Comparing B and C, though the component did not differ much, absolute value of the wind velocity did show a marked difference. Therefore, we consider that the perpendicular component of horizontal wind and wind velocity were associated with the development of the rainband. When a wind component perpendicular to the rainband is large, water vapor can be supplied easily and able to develop the rainband well. Although it was comparatively weak, the perpendicular component was also observed at SE as well as inside the rainband. Therefore we think that this wind behavior existed not as a result of the rainband generation but as the background field itself.

4 Concluding remarks

On 28–29 June 1999 and 1 July 2002 during the observation period of the X-BAIU-99 and -02, orographic rainbands, the Koshikijima line, extending northeastward from the Koshikijima Islands were observed. We have demonstrated the following features of the narrow rainbands.

The Koshikijima line observed in 1999 was maintained for 11 hours. It was well developed especially until 03:00 JST and was about 200 km in length and 20 km in width for 4 h from the beginning. The Koshikijima line observed in 2002 repeated development and decay for 11 h, and the maximum size of the precipitating area was about 120 km in length and 10 km in width.

Convectively unstable stratification was found below 3 km height. The Froude number averaged in a layer from the sea surface to the top of the Koshikijima Islands (~ 600 m) was large (> 1), and the LCL was below the tops of the mountains in the Koshikijima Islands. CAPE index was large enough to develop precipitating clouds and there was much water vapor in the lower layer. It is reasonable that upslope airflow in this layer can trigger convections forming the Koshikijima line.

While the Koshikijima line appears, strong southwesterly wind was dominant and the component of the horizontal wind perpendicular to the Koshikijima Islands (or the rainband) was large in the height range 1–3 km. This feature was observed almost everywhere inside the rainband. The wind direction in the height range became parallel to the Koshikijima Islands after the Koshikijima line decayed. We consider that the horizontal wind component parallel to the rainband blew convective cells, and the perpendicular component played the role of supplying water vapor to the rainband.

We have established a network observation method for orography-affected rainband system formation like the Koshikijima line, using wind profilers and weather radars. There are still many problems for the generating and developing mechanisms of the rainband system with the objective of scientific interests and social necessities like a disaster prevention.

Acknowledgements. The authors thank Dr. Masanori Yoshizaki and Dr. Teruyuki Kato of the Meteorological Research Institute, the Japan Meteorological Agency and X-BAIU observation members for providing the data, useful discussions and for their encouragement. The X-BAIU special observation was conducted mainly through funding from the Japan Science and Technology Corporation—Core Research for Evolutional Science and Technology. The first author (Y. Umemoto) is supported by a grant of the Japan Society for the Promotion of Science (JSPS) under the Fellowships for Japanese Junior Scientists. The present study was financially supported by Scientific Grants-in Aids of the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

- Akiyama, T.: Southerly transversal moisture flux into the extremely intense rainfall zone in the Baiu season, *J. Meteor. Soc. Japan*, 53, 304–316, 1975.
- Alexander, G. D. and Young, G. S.: The relationship between EMEX masoscale precipitation feature properties and their environmental characteristics, *Mon. Weath. Rev.*, 120, 554–564, 1992.
- Barnes, G. M. and Sieckman, K.: The environment of fast- and slow- moving tropical mesoscale convective cloud lines, *Mon. Weath. Rev.*, 112, 1782–1794, 1984.
- Houze Jr., R. A.: *Cloud Dynamics*, Academic Press, 570pp, 1993.
- Kato, T., Yoshizaki, M., Bessho, K., Inoue, T., Sato, Y., and X-BAIU-01 observation group: Reason for the failure of the simulation of heavy rainfall during X-BAIU-01—Importance of a vertical profile of water vapor for numerical simulations, *J. Meteor. Soc. Japan*, 81, 993–1013, 2003.
- LeMone, M. A., Zipser, E. J., and Trier, S. B.: The role of environmental shear and thermodynamic conditions in determining the structure and evolution of mesoscale convective systems during TOGA COARE, *J. Atmos. Sci.*, 55, 3493–3518, 1998.
- Matsumoto, S., Yoshizumi, S., and Takeuchi, M.: On the structure of the Baiu front and associated intermediate-scale disturbance in the lower atmosphere, *J. Meteor. Soc. Japan*, 48, 479–491, 1970.
- Ninomiya, K.: Characteristics of the Baiu front as a predominate subtropical front in the summer northern hemisphere, *J. Meteor. Soc. Japan*, 62, 880–894, 1984.
- Ninomiya, K.: Cloud distribution over East Asia during Baiu period in 1979, *J. Meteor. Soc. Japan*, 67, 639–658, 1989.
- Ninomiya, K.: Large- and Meso- α -scale characteristics of Meiyu-Baiu front associated with intense rainfalls in 1–10 July 1991, *J. Meteor. Soc. Japan*, 78, 141–157, 2000.
- Ninomiya, K.: Large γ -shaped cloud zone formed around 6 July 1991 with pole-ward moisture transport from intense rainfall area in Meiyu-Baiu front, *J. Meteor. Soc. Japan*, 79, 805–813, 2001.
- Smolarkiewicz, P. K. and Rotunno, R.: Low Froude number flow past three-dimensional obstacles. Part I: Baroclinically generated lee vortices, *J. Atmos. Sci.*, 46, 1154–1164, 1989.
- Smolarkiewicz, P. K. and Rotunno, R.: Low Froude number flow past three-dimensional obstacles. Part II: Upwind flow reversal zone, *J. Atmos. Sci.*, 47, 1498–1511, 1990.
- Umemoto, Y., Teshiba, M., Shibagaki, Y., Hashiguchi, H., Yamanaka, D. M., Fukao, S., and X-BAIU-99 and -02 observation groups: Combined wind profiler – weather radar observations of orographic rainband around Kyushu, Japan in the Baiu season, *Ann. Geophys.*, in press, 2004.
- Yoshizaki, M., Kato, T., Tanaka, Y., Takayama, H., Shoji, Y., Seko, H., Arao, K., Manabe, K., and Members of X-BAIU-98 Observation: Analytical and numerical study of the 26 June 1998 orographic rainband observed in western Kyushu, Japan, *J. Meteor. Soc. Japan*, 78, 835–856, 2000.
- Yoshizumi, S.: On the structure of intermediate-scale disturbances on the Baiu front, *J. Meteor. Soc. Japan*, 55, 107–120, 1977.