Genesis and Maintenance Processes of a Quasi-stationary Convective Band
that Produced Record-Breaking Precipitation
in Northern Kyushu, Japan on 5 July 2017

Tetsuya KAWANO and Ryuichi KAWAMURA

Department of Earth and Planetary Sciences, Kyushu University, Fukuoka, Japan

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Abstract

A quasi-stationary convective band that persisted for approximately ten hours caused precipitation in the northern part of Kyushu Island, Japan on 5 July 2017. The extreme amount of rainfall produced by this convective band caused a number of landslides and flash floods and resulted in a severe disaster. The Weather and Research and Forecasting (WRF) model was used to perform numerical simulations and to clarify the genesis and maintenance processes of the convective band. A full-physics WRF simulation successfully reproduced the observed features of the convective band and extreme precipitation. It was shown that a quasi-stationary convergence zone in the low level played a crucial role in generating and maintaining the convective band. Trajectory and frontogenesis analyses showed that low-level confluent flows due to the blocking effects of a high pressure system located over the Sea of Japan were responsible for the formation, intensification, and sustenance of the convergence zone. Furthermore, the frontal structure of the convergence zone was intensified due to the land-sea thermal contrast between Kyushu Island and the Tsushima Strait. Two additional experiments, namely a simulation with flattened topography of Kyushu Island and a simulation without considering raindrop evaporation also reproduced the observed band well. These results indicate that topography and a cold pool due to raindrop evaporation played only minor roles in the genesis and maintenance of the convective band.

Keywords     Baiu; extreme rainfall; quasi-stationary convective band; low-level convergence; confluent flow

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1. Introduction

Mesoscale convective systems (MCSs) are the primary precipitation producers in the Baiu season, which is the rainy season in East Asia including Japan. MCSs with band-shaped convective regions often cause torrential rainfall events. Unuma and Takemi (2016) investigated the organizational modes of quasi-stationary cloud clusters (QSCCs) during warm seasons from 2005 to 2012 and reported that 87% of the 2,549 selected QSCCs during that period exhibited elongated structures with aspect ratios greater than 1.4. Tsuguchi and Kato (2014) selected 386 cases of heavy rainfall during the warm seasons from 1995 to 2009 and showed that 64.4% of them exhibited band-shaped structures.

Many researchers have noted that back-building (BB) quasi-stationary precipitation systems, which are a type of band-shaped MCSs, have great potential for producing heavy rainfall within small areas. Ogura (1991) listed torrential rainfall events in Japan and
documented that most cases were caused by BB-type MCSs, even under different synoptic conditions. Schumacher and Johnson (2005) investigated the morphology of MCSs which produced extreme rainfall amounts east of the Rocky Mountains in the United States from 1999 to 2005. They noted two frequent organizational modes of the MCSs: training line/adjoining stratiform systems and back-building/quasi-stationary MCSs.

The formation, development and maintenance processes of BB-type systems which produced huge rainfall amounts in Japan have been examined in many previous studies (e.g., Watanabe and Ogura 1987; Kato 1998, 2006; Seko et al. 1999; Kato and Goda 2001). All of these studies have emphasized that the formation and intensification of quasi-stationary convergence is very important for the genesis, development and maintenance of BB-type precipitation systems.

Topography largely influences low-level winds and often produces convergence in the vicinity of the topography. Orographically forced convergence tends to stagnate because the topography remains fixed. Watanabe and Ogura (1987) analyzed a heavy rainfall incident that occurred in Shimane Prefecture in the western part of Japan on 23 July 1983 and showed that orographically induced convergence was responsible for the maintenance of a BB-type precipitation system that caused the torrential rainfall.

It is well known that the low-level cold pool produced by an MCS is very important in the development and maintenance of the MCS. Nagata and Ogura (1991) performed a numerical investigation of a heavy rainfall event that occurred on 23 July 1982 and concluded that a low-level cold pool associated with raindrop evaporation played an important role in the formation and development of the convective system. In contrast, Kato (1998) and Kato and Goda (2001) reported that raindrop evaporation only infrequently occurs in moist environments during the Baiu season, and therefore, no cold pool forms. On the basis of numerical simulations performed without considering raindrop evaporation, they concluded that raindrop evaporation has only a small impact on the formation and maintenance of convective systems that produce heavy rainfall. Schumacher (2009) also concluded, based on the results of idealized numerical experiments, that the mechanism for organizing heavy-rain-producing convective lines in moist environments is not a cold pool.

It has been observed that the mesoscale low-level convergence not associated with either topography or a cold pool is important for the formation and maintenance of BB-type convective systems. Kato (1998) carried out numerical simulations of a BB-type system that produced very large amounts of precipitation at Kagoshima, Japan on 1 August 1993. He attributed the maintenance of the BB-type precipitation system to a relatively large temperature gradient with horizontal convergence within the Baiu frontal zone. Based on the results of their numerical simulations, Kato and Goda (2001) concluded that the intensification of low-level upstream convergence by a BB-type convective band that produced heavy rainfall in Niigata Prefecture, Japan, largely contributed to the maintenance of the BB-type system. Kim and Lee (2016) investigated the formation process of a BB-type rainband that occurred over the Yellow Sea using a numerical model and demonstrated the importance of confluent flows associated with a trough to the formation and maintenance of the rainband.

A severe disaster caused by record-breaking precipitation occurred in the northern part of Kyushu Island, Japan, on 5 July 2017 (Fig. 1). The 6-hour accumulated rainfall (hereafter referred to as 6HAR) exceeded 600 mm. This was an extraordinary case unlike any we had ever experienced before. According to radar observations by the Japan Meteorological Agency (JMA), most of the precipitation was produced by a BB-type quasi-stationary convective band (hereafter referred to as BB-QSCB) that persisted from 1100 JST (Japan standard time; UTC + 9 hours) to 2200 JST. The objective of this study is to clarify the genesis and maintenance processes of this BB-QSCB using a numerical model. The simulations began more than 20 hours before the genesis of the BB-QSCB to reproduce the formation of low-level convergence. Thus, we not only discuss the genesis and maintenance processes of the BB-QSCB but also the formation process of the low-level convergence.

This paper is organized as follows. An overview of the torrential rainfall event and weather conditions is presented in Section 2. Section 3 documents the numerical model and experimental design used in this study. The results of the control and sensitivity experiments are presented in Sections 4 and 5, respectively. Finally, a summary and conclusions are presented in Section 6.

2. Case overview

The daily accumulated rainfall at the JMA Asakura AMeDAS (Automated Meteorological Data Acquisition System) station on 5 July 2017 reached 516 mm (Fig. 2a). Most of this rainfall was recorded between
1100 JST and 2200 JST. A maximum hourly accumulated rainfall amount of 129.5 mm was observed between 1500 JST and 1600 JST. Figure 2b shows the distribution of 6HAR from 1200 JST to 1800 JST on 5 July 2017 which was obtained from the JMA radar rain-gauge analyzed precipitation data. In the figure, an area with 6HAR exceeding 100 mm extends approximately 50 km and 30 km in the zonal and meridional directions, respectively. One of the most prominent features in the rainfall distribution is that the 6HAR levels greater than 400 mm are restricted to within a very narrow region. The maximum 6HAR of 660 mm was recorded at a location just to the east of the Asakura station.

Figure 3 shows the JMA surface weather charts at 0900 JST, 1500 JST and 2100 JST on 5 July 2017. The North Pacific subtropical high, which stagnated in the south of Japan, extended to the East China Sea. On the other hand, a synoptic high was located at the northern part of the Korean Peninsula at 0900 JST on 5 July 2017 and slowly moved southeastward. Subsequently, from 1500 JST to 2100 JST on 5 July 2017, the high stagnated over the Sea of Japan and its southwestern part intensified. A Baiu front located between these synoptic high pressure systems extended from the southern part of the Korean Peninsula to the Pacific Ocean east of Japan. The Baiu front near the western part of Honshu Island moved southwestward very slowly.

The National Centers for Environmental Prediction (NCEP) Final Operational Global Analysis (FNL)
data revealed a favorable environment for the occurrence of heavy rainfall in northern Kyushu. As shown in Figs. 4d–f, southwesterlies associated with the North Pacific high continued to advect large amounts of water vapor from the East China Sea to the northern part of Kyushu Island. In addition, northern Kyushu was located in front of an upper-level large potential vorticity moving eastward (Figs. 4a–c). This situation may have led to upward motion in northern Kyushu (e.g., Hoskins et al. 1985; Hirota et al. 2016). The mlCAPE (mixed-layer convective available potential energy) and SReH (storm relative helicity in the lowest 3 km) calculated from JMA MANAL (Mesoscale ANALysis) at 1200 JST on 5 July 2017 exhibited approximately 2,100 J kg$^{-1}$ and 100 m$^2$s$^{-2}$ in the upstream region in northern Kyushu, respectively. Thus, the environment around northern Kyushu was very favorable for the initiation and development of deep convection.

A BB-QSCB that produced extreme precipitation amounts developed in the area around the northern part of Kyushu Island under these conditions. Figure 5a shows a time sequence of rainfall intensities observed by JMA operational radar between 1100 JST and 2200 JST on 5 July 2017. After 1100 JST on 5 July 2017, several cumulonimbi were initiated and then organized as a BB-QSCB by 1300 JST. The BB-QSCB exhibited single or double line-shaped structures during its existence. The heaviest rainfall intensity was recorded between 1500 JST and 1600 JST. This was the same time interval during which the maximum hourly accumulated rainfall of 129.5 mm was recorded at the Asakura AMeDAS station (Fig. 2a). The BB-QSCB persisted until approximately 2200 JST. As a result, the duration of the BB-QSCB was longer than 10 hours.

3. Numerical model and experimental design

The model used in this study is the Weather Research and Forecasting (WRF) model (Skamarock et al. 2008), version 3.7.1. To capture mesoscale to synoptic-scale phenomena, three domains with two-way nesting were adopted (Fig. 1). The horizontal grid spacings of domains 1 (D1), 2 (D2), and 3 (D3) were 9, 3, and 1 km, respectively. All domains had 40 vertically stretched grids from the surface to 50 hPa. The physics parameterizations used include the land surface scheme proposed by Chen and Dudhia (2001), planetary boundary scheme proposed by Hong et al. (2006) and Hong (2010), shortwave radiation scheme proposed by Dudhia (1989), and longwave radiation scheme proposed by Mlawer et al. (1997). This study employed the Milbrandt-Yau two-moment microphysics scheme (Milbrandt and Yau 2005) for all domains. In addition, the Kain–Fritsch cumulus parameterization scheme (Kain and Fritsch 1990, 1993) was adopted for D1 and D2. The model was initiated at 1500 JST on 4 July 2017 and was integrated for up to 36 hours. To discuss the genesis process as well as the maintenance process of the BB-QSCB, the simulations were started more than 20 hours before the occurrence of the BB-QSCB. The initial and boundary conditions were obtained from the 6-hourly NCEP FNL data with a horizontal resolution of 1.0° × 1.0°. This control simulation is hereafter referred to as CNTL.

To examine the effects of topography and raindrop evaporation on the genesis, development, and maintenance processes of the BB-QSCB, two additional experiments were carried out. One was a simulation with flattened topography for Kyushu Island and its
surrounding islands (hereafter referred to as FLATK), for which the elevation within the rectangle from 128.5–132.1°E and 30.0–34.0°N was set to zero. The other was a simulation without raindrop evaporation (hereafter referred to as NOEVP).

4. Control simulation

4.1 Validation of the simulation

We checked the reproducibility of the CNTL simulation. Figure 5b shows a time sequence of rainfall intensities simulated for CNTL from 1100 JST to 2200 JST on 5 July 2017. By comparing the simulation results with the observed BB-QSCB, we found that the genesis of the CNTL-simulated QSCB was delayed by approximately one hour and that its position shifted slightly east-northeastward. In addition, the CNTL-simulated convective band exhibited only a single line-shaped structure throughout the duration of the QSCB. Despite these differences, the evolution of the CNTL-simulated QSCB was very similar to that of the observed one. The CNTL-simulated rainband developed primarily between 1500 JST and 1800 JST. Very large amounts of rainfall fell within a small area (Fig. 2c). These features also agree well with the observations. In addition, the CNTL-simulated maximum 6HAR of 629 mm between 1200 JST and 1800 JST on 5 July 2017 is comparable to the observed maximum 6HAR of 660 mm (Figs. 2b, c). Therefore, we believe that the CNTL simulation reproduced the observations very well.

The CNTL-simulated QSCB exhibited a BB-type organization mode, as shown in Fig. 6. New convective cells were repeatedly initiated on the upstream (i.e., western) side. A new cell was generated at approximately 130.6°E and then rapidly developed and moved eastward. The cell reached its peak development in the middle region of the BB-QSCB. At that time, the cloud top heights exceeded 16 km. These features are consistent with observations by the XRAIN (eXtended RAdar information Network) of the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) (not shown). The maximum updrafts...
Fig. 5. Time sequences of rainfall intensities (color shading; mm h⁻¹) from 1100 JST 5 July to 2200 JST on 5 July 2017 at 1-hour intervals. (a), (b), (c), and (d) show radar-observed, CNTL-simulated, FLATK-simulated, and NOEVP-simulated rainfall intensities, respectively. The rainfall intensities simulated in D3 are displayed in (b), (c), and (d).
were greater than 30 m s\(^{-1}\) in the CNTL simulation, which shows that the cumulonimbi developed at a violent pace.

### 4.2 Evolution of low-level winds

Figure 7 shows the evolution of the 700-hPa total condensed water and 950-hPa winds simulated for CNTL. Southwesterlies were evident over northern Kyushu and the Tsushima Strait on the morning of 5 July 2017 (Figs. 7a–c). The flows changed into west-southwesterlies or westerlies north of the Tsushima Strait, over the western part of Honshu Island, and over the Seto Inland Sea. Weak northwesterlies, on the other hand, were evident over the western part of the Sea of Japan. A convergence zone formed at the boundary between the westerlies and northwesterlies. A band-shaped convective system was generated and developed in the convergence zone. The convective system, accompanied by the low-level convergence, moved very slowly southeastward. The evolution of the convective system was consistent with the observations (not shown).

As shown in Figs. 7d–f, between 1200 JST and 1300 JST on 5 July 2017, the convective system reached the Seto Inland Sea. At the same time, low-level southwesterlies and west-southwesterlies flowed together in the area of the northern part of Kyushu Island and a new low-level convergence zone formed there. A BB-QSCB that produced extreme precipitation occurred along this convergence zone (Fig. 7f). The convergence was sustained until nighttime. As a result, the BB-QSCB developed violently (Figs. 7g–i) and persisted until at least 2200 JST (see Fig. 5b). In contrast, the convective system located in the Seto...
Inland Sea eventually dissipated.

We conducted a forward trajectory analysis to confirm the evolution of low-level winds, as mentioned above. Figure 8 shows 12-hour forward trajectories of parcels located at a height of 250 m over the East China Sea. Because the forward trajectories of the parcels located at the lowest levels (i.e., below 500 m) exhibited similar features, those located at 250 m are shown here. As shown in Fig. 8a, between 2100 JST on 4 July 2017 and 0900 JST on 5 July 2017, the low-level parcels moved northeastward over the sea west of Kyushu Island. The parcels in the southern region (PSs) continued to move northeastward after reaching Kyushu Island. Some PSs were lifted by the topography of Kyushu Island. On the other hand, parcels in the northern region (PNs) moved east-northeastward or eastward after reaching the Tsushima Strait. Some PNs were elevated over the western part of the Sea of Japan and over the western part of Honshu Island and resulted in the formation of a convective system along a line located at approximately 34.7°N.

The twelve-hour forward trajectories starting at 0100 JST on 5 July 2017 are shown in Fig. 8b. The movement of the PSs was similar to that of PSs which started at four hours earlier but the trajectories of the PNs changed dramatically. The speed at which the PNs moved decreased when they passed the Tsushima Strait. In addition, the direction of the movement changed to east-southeastward. As a result, some PSs and PNs converged in the area around the northern part of Kyushu Island and were elevated to above 2
Fig. 8. 12-hour forward trajectories of parcels located at a height of 250 m within a black rectangle in (a) at (a, d) 2100 JST on 4 July 2017, (b, e) 0100 JST on 5 July 2017, and (c, f) 0500 JST on 5 July 2017 for the CNTL simulation. Colors in (a, b, c) and in (d, e, f) show heights (units; m) of the parcels and their potential temperatures (units; K), respectively. The variables simulated in D2 are used for the trajectory calculations.
km. This upward motion is associated with several cumulonimbi that organized as the BB-QSCB that produced extreme precipitation in that area.

Figure 8c shows the 12-hour forward trajectories starting at 0500 JST on 5 July 2017. It is very clear that the PN passing the southern part of the Tsushima Strait largely curved southeastward. The PSs, on the other hand, continued to move northeastward. The confluent flows located in the area of the northern part of Kyushu Island further intensified. These quasi-stationary confluent flows were responsible for sustaining the BB-QSCB.

The potential temperatures of the trajectories revealed a thermodynamic feature in the confluent region in northern Kyushu (Figs. 8e, f). The potential temperatures of PN passing the sea remained almost unchanged for the greater part of their trajectories. The potential temperatures of PSs changed very little while the PSs passed the sea. However, after they reached Kyushu Island, the potential temperatures greatly increased. Sensible heat fluxes from the land surface are responsible for the warming of the PSs because no moist convection existed in the warming area. Consequently, the convergence region between the PN and PS had a frontal feature, which will be further discussed in Section 5.2.

We investigated the cause of the drastic changes in low-level winds around northern Kyushu. Figures 9a–d show the CNTL-simulated geopotential heights at 950 hPa at 0900 JST, 1200 JST, 1500 JST, and 1800 JST, respectively on 5 July 2017. At 1200 JST, the geopotential heights began to increase in the southwestern part of the Sea of Japan compared to those at 0900 JST. These heights subsequently continued to increase. The evolution of geopotential heights is consistent with the high pressure system that was located over the northern part of the Korean Peninsula and initially moved slowly southeastward followed by stagnation and intensification, as shown in JMA surface weather charts (Fig. 3).

There were large differences in the low-level winds between 0900 JST and 1500 JST on 5 July 2017. In particular, drastic changes in the low-level winds were detected around western Honshu and northern Kyushu. The low-level winds changed direction from east-northeastward to southeastward. In other words, the high pressure system stagnated and increased in pressure over the Sea of Japan and thus blocked the low-level westerlies and dramatically changed the low-level wind field.

Figures 9e–h show the CNTL-simulated temperatures at 950 hPa at 0900 JST, 1200 JST, 1500 JST and 1800 JST, respectively on 5 July 2017. There was a relatively large temperature gradient around western Honshu, northern Kyushu, and southwest of the Sea of Japan, which corresponded to the Baiu frontal zone. At 1200 JST, the air over Kyushu Island was heated by large sensible heat fluxes from the land surface (Fig. 9f). As a result, the temperature gradients were intensified by the differential heating between land and sea, especially along the coastline of northern Kyushu. At 1500 JST and 1800 JST (Figs. 9g, h), for the period in which the confluent flows intensified and were maintained, a frontal structure with a relatively large temperature gradient formed in the confluent region, which will be further discussed in Section 5.2.

5. Sensitivity experiments

5.1 Orographic effects

Previous studies (e.g., Watanabe and Ogura 1987; Yoshizaki et al. 2000) have demonstrated that orographic effects are important for the formation and maintenance of BB-QSCBs. A simulation with a flattened topography for Kyushu Island and its surrounding islands (FLATK) was performed to examine orographic effects on the formation and maintenance of the subject BB-QSCB that produced extreme precipitation in northern Kyushu. Figure 5c shows a time sequence of rainfall intensities simulated for FLATK. The FLATK experiment also reproduced the BB-QSCB. In comparison with the CNTL simulation, the occurrence of the BB-QSCB was delayed by approximately two hours and its position shifted slightly southeastward. However, the rainfall area and intensity were comparable to those simulated for CNTL. In addition, the FLATK-simulated BB-QSCB persisted for longer than 10 hours. We therefore concluded that the topography of Kyushu Island was not necessarily important for the formation and maintenance of the BB-QSCB.

The evolution of the 700-hPa total condensed water and 950-hPa winds simulated for FLATK are shown in Fig. 10. A comparison of these results with the CNTL simulation results reveals only small differences in the BB-QSCB features between the CNTL and FLATK

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1 An additional experiment without Kyushu Island, in which the island was changed to the sea, reproduced no precipitation systems in the corresponding area. It seems that the land-sea thermal contrast between Kyushu Island and its surrounding sea influenced the formation of the low-level convergence and the resulting genesis of the BB-QSCB. In this study, however, we will not discuss the thermal contrast effect further because a detailed investigation of the effect is beyond the scope of this study.
Fig. 9. (a–d) CNTL-simulated geopotential height (color shading; m) and (e–h) temperature (color shading; °C) at 950 hPa at (a, e) 0900 JST, (b, f) 1200 JST, (c, g) 1500 JST, and (d, h) 1800 JST on 5 July 2017. Vectors indicate 950-hPa winds (m s$^{-1}$). The variables simulated in D2 are displayed in all panels.
scenarios. In addition, the evolution of low-level winds simulated for FLATK was similar to that simulated for CNTL. However, we detected differences in the low-level winds between CNTL and FLATK in the area around the western part of Kyushu Island. The CNTL-simulated winds were southwesterlies, whereas the FLATK-simulated winds were west-southwesterlies (Figs. 7, 10). These differences seem to be attributable to the barrier effect of the Kyushu topography. The CNTL-simulated low-level winds on the upstream side detoured due to the barrier effect. The resulting southwesterlies promoted the formation of the low-level convergence for CNTL. Consequently, in the FLATK simulation, the maximum 6HAR between 1500 JST and 2100 JST on 5 July 2017 was 547 mm, which was smaller than that seen in the CNTL simulation. We therefore concluded that the topography of Kyushu Island contributed to the BB-QSCB development and precipitation increase to some extent. These findings are partially consistent with the observation of Takemi (2018) that, for the same case, a simulation with more realistic topography reproduces the observed precipitation better than a simulation with lower-resolution topography.

Fig. 10. As in Fig. 7 except for the FLATK simulation.

3The FLATK-simulated BB-QSCB occurred after a delay of two to three hours compared to the CNTL-simulated BB-QSCB.
5.2 Frontogenesis analysis

As mentioned above, a low-level frontal structure associated with the confluent flows formed and intensified in the area of northern Kyushu Island. To further investigate how the convergence zone with the frontal structure formed, a frontogenesis analysis was conducted. The frontogenesis function may be written as follows:

$$
\frac{d}{dt} \nabla_h \theta = -\frac{1}{\nabla_h \theta} \left\{ \left( \frac{\partial \theta}{\partial x} \right)^2 \frac{\partial u}{\partial x} + \left( \frac{\partial \theta}{\partial y} \right)^2 \frac{\partial v}{\partial y} \right\} - \frac{1}{\nabla_h \theta} \left( \frac{\partial \theta}{\partial y} \right) \frac{\partial u}{\partial x} + \frac{1}{\nabla_h \theta} \left( \frac{\partial \theta}{\partial x} \right) \frac{\partial v}{\partial y} + \frac{1}{\nabla_h \theta} \left( \frac{\partial \theta}{\partial y} \right) \frac{\partial \theta}{\partial y} \frac{\partial \theta}{\partial t},
$$

(1)

where $u$, $v$, and $w$ are the zonal, meridional, and vertical winds, respectively; $\theta$ is the potential temperature; $\nabla_h$ is the horizontal derivative at constant height; and the first, second, third, and fourth terms on the right-hand side of Eq. (1) are the confluence, shearing, tilting and diabatic terms, respectively.

The low-level frontogenesis function, which is the most interesting for the purposes of this study, could not be calculated from the CNTL simulation results because of the complicated topography. Therefore, we used the FLATK results because the features of the BB-QSCB and the low-level winds for FLATK were very similar to those for CNTL. Figures 11a–e show each term in the frontogenesis function at a height of 300 m at 1500 JST on 5 July 2017 when the BB-QSCB was in the early development stage. Figure 11a shows that a frontogenesis occurred along the convergence zone in northern Kyushu. Although the diabatic term made a positive contribution, the confluence term dominates in its contribution to the frontogenesis (Figs. 11b, e). As mentioned above, the confluent flows were related to the drastic change in low-level winds. On the other hand, the shearing term was small (Fig. 11c). In contrast, the tilting term provided both positive and negative contributions (Fig. 11d).

The evolution of each term in the frontogenesis function, averaged with respect to the BB-QSCB, is shown in Fig. 11f. The tilting term was negative from 1300 JST to 1600 JST on 5 July 2017, which is the interval that corresponds to the formation and development stages of the BB-QSCB (see Fig. 5c). A negative tilting term means that active convection occurred on the relatively warm (i.e., southern) side. The confluence, shearing, and diabatic terms provided positive contributions to the frontogenesis. In particular, after 1400 JST, the confluence term was dominant over the other terms. Thus, the frontogenesis analysis results confirm that confluent flows played a significant role in the formation and maintenance of the quasi-stationary convergence zone with the frontal structure.

5.3 Roles of the convectively induced cold pool

To investigate the effects of a cold pool caused by raindrop evaporation on the formation, development, and maintenance processes of the BB-QSCB that produced extreme precipitation in northern Kyushu, a simulation without the raindrop evaporation process (NOEVP) was carried out. A time sequence of the NOEVP-simulated rainfall intensities is shown in Fig. 5d. The NOEVP simulation reproduced the BB-QSCB. In the NOEVP simulation, the BB-QSCB formed at nearly the same time as in the CNTL simulation although it dissipated approximately two hours earlier. The maximum 6HAR between 1200 JST and 1800 JST on 5 July 2017 in the NOEVP simulation was 740 mm, which is greater than that in the CNTL simulation. The reason for this is that raindrops below the cloud base reached the surface without evaporation in the NOEVP simulation.

The CNTL-simulated horizontal divergence at 950 hPa is shown in Figs. 12a–c. In addition, the 950-hPa temperature differences between CNTL and NOEVP are shown in Figs. 12d–f. At 1300 JST on 5 July 2017, the time at which the BB-QSCB started to form, we detected a low-level convergence but no cold pool (Figs. 12a, d). In the developing stage of the BB-QSCB at 1500 JST, the low-level convergence intensified on the upstream (i.e., western) side of the BB-QSCB and a cold pool with a maximum temperature drop of approximately 3°C was detected on the downstream (i.e., eastern) side (Figs. 12b, c). Thus, the relationship between the cold pool and low-level convergence is obscure. These features suggest that the convectively induced cold pool played only a minor role in the formation and development of the BB-QSCB, which is consistent with the results reported by Kato (1998) and Kato and Goda (2001).

In the latter stage of the existence of the BB-QSCB, however, low-level convergence formed along a cold pool located on the southwestern flank of the BB-QSCB (Figs. 12c, f). In addition, the NOEVP-simulated BB-QSCB dissipated approximately two hours earlier than the CNTL-simulated BB-QSCB (Figs. 5b, d). Thus, the convectively induced cold pool may have contributed to maintaining the BB-QSCB in
Fig. 11. Frontogenesis function (color shading: K km$^{-1}$ h$^{-1}$) and winds (vectors; m s$^{-1}$) at a height of 300 m at 1500 JST on 5 July 2017 for the FLATK simulation. (a) Total frontogenesis, (b) confluence term, (c) shearing term, (d) tilting term, and (e) diabatic term. (f) Temporal evolution of each frontogenesis term averaged within a green rectangle in (a–e) panels. The black line indicates total frontogenesis. The red, green, blue, and orange lines indicate the confluence, shearing, tilting, and diabatic terms, respectively. The variables simulated in D2 are displayed in all panels.
A back-building quasi-stationary convective band (BB-QSCB) occurred in the area of the northern part of Kyushu Island on 5 July 2017. It persisted for more than ten hours and produced record-breaking precipitation, thereby resulting in a severe disaster. This study investigated the genesis and maintenance processes of the BB-QSCB. A schematic diagram illustrating the processes is shown in Fig. 13.

The surface weather charts showed two synoptic high pressure systems. One was the quasi-stationary North Pacific subtropical high. The other was located in the area of the northern part of the Korean Peninsula during the morning of 5 July 2017. It slowly moved southeastward and then stagnated over the Sea of Japan. In addition, the high intensified. A Baiu front was formed between these two high pressure systems. At the low levels, large amounts of water vapor were advected into northern Kyushu by southwesterlies associated with the North Pacific subtropical high. In addition, northern Kyushu was located in front of an upper-level large potential vorticity. The mlCAPE and SReH were approximately 2,100 J kg$^{-1}$ and 100 m$^2$ s$^{-2}$, respectively on the upstream side of the subject region. This synoptic environment was very favorable for the occurrence of active convection.

In this environment, several cumulonimbi were generated after 1100 JST on 5 July 2017. Subsequently, they organized into a BB-QSCB by 1300 JST. The BB-QSCB reached its peak between 1500 JST and 1600 JST. During this period, a maximum hourly accumulated rainfall of 129.5 mm was recorded at the Asakura AMeDAS station. In addition, the maximum 6-hour accumulated rainfall (6HAR) between 1200 JST and 1800 JST on 5 July 2017 reached 660 mm just to the east of the Asakura station. The BB-QSCB persisted for at least ten hours.

To investigate the genesis and maintenance processes of the BB-QSCB, we performed numerical simulations using the WRF model. The CNTL simulation reproduced the observed BB-QSCB very well. New cells continued to form on the upstream side and developed rapidly as they moved eastward. The maximum updraft exceeded 30 m s$^{-1}$ in the middle portion of the BB-QSCB. The CNTL-simulated maximum 6HAR of 629 mm from 1200 JST to 1800 JST on 5
July 2017 was comparable to the observed one. A forward trajectory analysis showed the formation and intensification of a convergence zone with a frontal structure due to drastic changes in low-level winds. The twelve-hour forward trajectories of parcels located over the East China Sea on the night of 4 July 2017 showed that the parcels moved northeastward and reached the western part of the Sea of Japan and western Honshu, Japan. In contrast, after portions of parcels established during the early morning of 5 July 2017 reached the Tsushima Strait, their movement direction changed to east-southeastward or southeastward. In addition, their potential temperatures were almost unchanged because of travel over the sea for most of their trajectories. Other parcels continued to move northeastward over the East China Sea and western Kyushu. The potential temperatures of the parcels were largely increased by the sensible heat fluxes from the land surface after reaching Kyushu Island. These converged in the area around the northern part of Kyushu Island, resulting in the formation of a convergence zone with a frontal feature, which played a significant role in the genesis and maintenance of the BB-QSCB.

The stagnation and intensification of the high pressure system located over the Sea of Japan was responsible for the dramatic changes in low-level winds. The high located over the northern part of the Korean Peninsula at 0900 JST on 5 July 2017 moved slowly southeastward and then stagnated and intensified over the Sea of Japan. This high played an important role in blocking the southwesterlies passing the Tsushima Strait. As a result, the southwesterlies changed to west-northwesterlies or northwesterlies.

A simulation conducted with flattened topography for Kyushu Island and its surrounding islands (FLATK) showed that the topography of Kyushu was not necessarily important for the formation and maintenance of the BB-QSCB. The barrier effect of the Kyushu topography, however, enhanced the northerly component of the low-level winds in the western part of Kyushu Island and resulted in the intensification of the low-level convergence in the northern part of Kyushu Island. Consequently, the CNTL-simulated BB-QSCB developed further and then produced more precipitation than the FLATK-simulated BB-QSCB.

To examine how the low-level convergence with the frontal structure formed and intensified, we conducted a frontogenesis analysis using the results of the FLATK simulation. The analysis results showed that the confluence term associated with the blocking of low-level winds mainly contributed to the frontogenesis associated with the BB-QSCB. In contrast, the tilting term had a negative effect on the frontogenesis.

Fig. 13. Schematic diagram of the genesis and maintenance processes of the quasi-stationary convective band that produced record-breaking precipitation in northern Kyushu on 5 July 2017. Arrows indicate low-level flows.
To investigate the role of a cold pool caused by raindrop evaporation on the formation and maintenance of the BB-QSCB, a simulation without raindrop evaporation (NOEVP) was performed. Raindrop evaporation was found to have a small impact on the formation and intensification of the BB-QSCB. However, the duration of the NOEVP-simulated BB-QSCB was approximately two hours shorter than that of the CNTL-simulated one. We concluded from this that the convectively induced cold pool may have influenced the maintenance of the BB-QSCB in its latter stages.

We emphasize that the blocking of low-level winds by the high pressure system located over the Sea of Japan played a significant role in the formation and maintenance of the quasi-stationary convergence zone and that the topography of Kyushu Island and a convectively induced cold pool had only minor influences. The convergence zone formed under the environment of confluence resulting from blocking by the high. Because the high stagnated and intensified over the Sea of Japan, the low-level convergence became long-lived and quasi-stationary. Consequently, the quasi-stationary convergence promoted the genesis, development, and maintenance of the BB-QSCB.

It is beyond the scope of this study to clarify the cause of the stagnation of the synoptic high located over the Sea of Japan. Future work requires understanding synoptic- and larger-scale phenomena and their interactions that controlled the migration of the high pressure system.

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