Characteristics of Atmospheric Environments of Quasi-Stationary Convective Bands in Kyushu, Japan during the July 2020 Heavy Rainfall Event

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Abstract

This study investigated characteristics of atmospheric environmental fields in the occurrence of quasi-stationary convective bands (QSCBs) in Kyushu, western Japan during the July 2020 heavy rainfall event. We performed case studies of extreme rainfall subevents in the Kumamoto and Kagoshima prefectures on 3−4 July (2020KK) and northern Kyushu on 6−7 July 2020 (2020NK), compared with two heavy rainfall events in northern Kyushu in 2017 and 2018.

Nine QSCBs were objectively extracted during the July 2020 heavy rainfall event, causing hourly precipitation amounts exceeding 100 mm twenty times. In 2020KK, the environmental field with extremely large precipitable water due to low-level and middle-level humidity was affected by the upper-level cold airflow, which resulted in favorable condition for the deep convection development. Consequently, the lightning activity became high, and cloud tops were the highest in comparison to previous events. QSCBs in 2020KK and 2020NK were located along a low-level convergence line/zone associated with an inflow that had extremely large water vapor flux on the south side of the mesoscale Baiu frontal depressions. In most of the QSCB cases in 2020, mesoscale depressions were observed and enhanced horizontal winds, which led to extremely large low-level water vapor flux to produce short-term heavy rainfall.

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1. Introduction

In early July 2020, extreme rainfall occurred in Kyushu, western Japan, which named “the July 2020 heavy rainfall event”, causing extensive damages due to floods and landslides. It is well known that heavy rainfall occurs in Kyushu during the Baiu season, the rainy season from mid- to late spring through early to midsummer in Japan (e.g., Akiyama 1973; Ogura et al. 1985; Nagata and Ogura 1991; Moteki et al. 2004a, b), and quasi-stationary convective bands (hereafter QSCBs) often cause heavy rainfall (Ogura 1991; Yoshizaki et al. 2000; Kato 1998, 2005, 2006). Statistical studies have indicated that precipitation systems corresponding to QSCBs occur frequently in Kyushu (Tsuguti and Kato 2018; Unuma and Takemi 2016a, b; Hirockawa et al. 2020a). QSCBs are often called “Senjo-kousuitai” in Japanese, and can cause extreme rainfall and extensive damages (Kato 2020).

In previous studies on the environmental occurrence conditions for heavy rainfall, environmental parameters including stability indices have been used to quantify the conditions (Kato et al. 2007; Kato 2011; Araki et al. 2017; Takemi and Unuma 2019). The difference between the environmental occurrence conditions for quasi-stationary convective clusters and the other precipitation systems during the warm seasons in Japan has been statistically clarified using environmental parameters (Unuma and Takemi 2016a, b), Kato (2020) proposed environmental conditions, including dynamic and thermodynamic environmental parameters and low-level water vapor flux, for the diagnostic forecast of QSCBs by examining those in previous cases of localized heavy rainfall events. While such diagnostic approaches are useful for statistically standardizing environmental occurrence conditions for QSCBs, it is arguable whether or not they could apply to extreme cases that have resulted in heavy rainfall disasters in recent years.

Some case studies have been conducted on extreme rainfall cases caused by QSCBs in recent years. In “the July 2017 northern Kyushu heavy rainfall event” occurred in northern Kyushu on 5−6 July 2017, cumulonimbus clouds developed higher than 15 km, which were caught by radar observations (Kato et al. 2018). Kawano and Kawamura (2020) showed that a low-level quasi-stationary convergence zone played a crucial role in forming and maintaining the QSCB. Extreme rainfall was also caused by QSCBs in northern Kyushu during “the July 2018 heavy rainfall event” (Shimpo et al. 2019; Tsuguti et al. 2019). It is noted that the environmental fields in this event were characterized by synoptic-scale ascent that were induced by an upper trough (Takeumra et al. 2019; Sekizawa et al. 2019; Yokoyama et al. 2020), synoptic-scale or larger moisture flow (Yatagai et al. 2019), and extremely large amounts of precipitable water due to a very humid environment in the middle-level atmosphere (Takemi and Unuma 2019). Tsuji, et al. (2020) compared environmental fields in the 2017 and 2018 events, and noted that the middle-level atmosphere was moist in the latter due to synoptic-scale ascent dynamically forced by a deep trough. They also noted that upper-level cold air advection due to a shallow trough enhanced atmospheric instability in the 2017 event.

On the other hand, it has been known that mesoscale Baiu frontal depressions (BFDs), which are the mesoscale depressions developing over the Baiu front, are important for the environmental occurrence conditions for heavy rainfall in Kyushu (Akiyama 1984; Ninomiya et al. 1984; Ogura et al. 1985; Ninomiya 1978, 2000; Ninomiya and Yamazaki 1979). Ogura et al. (1985) performed a case study on “the Nagasaki heavy rainfall event” that occurred in northern Kyushu on 23 July 1982, and showed that the QSCB-like precipitation intensification appeared during the period when very moist low-level inflow reached peak near the mesoscale BFD. They also noted that localized heavy rainfall occurred over several other areas in association with mesoscale BFDs and the precipitation intensified over coast areas upwind of moist low-level jets.

Moreover, only a few studies have investigated extreme cases causing heavy rainfall disasters in recent years using the diagnostic approach with environmental parameters. Therefore, to characterize the atmospheric environments for the occurrence of extreme rainfall caused by QSCBs during the July 2020 heavy rainfall event, we performed case studies of extreme rainfall subevents in Kumamoto and Kagoshima prefectures on 3−4 July (2020KK) and northern Kyushu on 6−7 July 2020 (2020NK), comparing them with the extreme rainfall events on 6−7 July 2018 (2018NK) and on 5 July 2017 (2017NK) focusing on the importance of mesoscale BFDs using environmental parameters derived from analysis data.

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2. Data and methods

First, QSCBs in each event were objectively extracted using the method of Hirockawa et al. (2020a), which identified and classified heavy rainfall areas into four types (linear-stationary, linear, stationary, and others) with defining criteria such as aspect ratio, overlap ratio, and duration from distributions of accumulated three-hour precipitation amounts derived from the Japan Meteorological Agency (JMA) radar/raingauge-analyzed precipitation amounts (RA; Nagata 2011). In this study, linear-stationary heavy rainfall areas were extracted as QSCBs (details are described by Hirockawa et al. 2020a, b). Periods for the QSCB extraction were set from 12:00 JST (JST = UTC + 9 hours) 3 July to 12:00 JST 8 July 2020, from 00:00 JST 5 July to 00:00 JST 9 July 2018, and from 00:00 JST 4 July to 06:00 JST 6 July 2017. Nine, four, and one QSCBs were extracted in Kyushu during the events of 2020, 2018, and 2017, respectively (Table 1). Occurrence distribution of QSCBs in the 2020 event is shown in Fig. S1 in Supplement. For case studies on the environmental occurrence conditions for each QSCB, the JMA RA data, local analysis (LA) data (JMA 2019), and the Himawari-8 satellite data (Bessho et al. 2016) were used in this study.

Second, characteristics of precipitation amounts and atmospheric environmental fields during the periods from 00:00 JST 3 July to 06:00 JST 6 July 2020, from 00:00 JST 5 July to 06:00 JST 7 July 2018, and from 00:00 JST 4 July to 06:00 JST 6 July 2017 are shown in Figs. 2 and 3. These events caused heavy rainfall caused by QSCBs. Environmental conditions even during extreme rainfall events. Temperature at 250 and 500 hPa (T_250, T_500), advection of temperature at 250 and 500 hPa (TAADV_250, TADV_500), and vertical velocity at 700 hPa (W_700) were averaged during the periods of QSCBs and others, respectively. For the cases of the QSCBs, it has been confirmed that the locations of the occurrence of R_1max and QSCBs are consistent with each other by checking the distributions of hourly precipitation amount at each time.

3. Results

3.1 Precipitation characteristics of QSCBs

To reveal the contribution of QSCB on precipitation amounts during extreme rainfall events, the occurrence frequencies of R_1max classified by precipitation amounts in Kyushu were examined (Fig. 1). During the 2020 event, huge R_1max exceeding 100 mm h^{-1} is observed twenty times, all of which are caused by QSCBs. Moreover, R_1max values of 80 mm or more are caused at rates of 97%, 58%, and 60% by QSCBs in the 2020, 2018, and 2017 events, respectively. These results show that the rate of short-term heavy rainfall caused by QSCBs is notably higher in the 2020 event than those in the 2017 and 2018 events.

3.2 Case studies on 2020KK and 2020NK

Environmental fields of QSCBs in 2020KK and 2020NK are shown in Figs. 2 and 3, respectively. Upper-level cold air flows to Kyushu, found in the rear of an upper-level trough at 250 hPa (Fig. 2a), and the middle-level warm air advection associated with a middle-level trough is found in the west of Kyushu at 500 hPa (Fig. 2b). The synoptic-scale moisture flow with very large PWV, which is traditionally called a “moist tongue” (e.g., Akiyama 1973; Kato et al. 2003) or recently “atmospheric river” (e.g., Kamae et al. 2017; Yatagai et al. 2019), is found in the south of the Baiu front, and a mesoscale depression is observed over the Baiu front just.
below the middle-level trough (Fig. 2c). This depression forms in the front of the middle-level trough at 09:00 JST on 3 July, travelling eastward without intense precipitation around the center of the depression (Fig. S3 in Supplement). This feature is consistent with typical BFDs (Akiyama 1984; Ogura et al. 1985; Tochimoto and Kawano 2012, 2017). The QSCB is located along a convergence line between the circulation associated with the BFD and the flow along the edge of the Pacific high, associated with the inflow that has significantly large low-level water vapor flux (Fig. 2d). The CTT of the QSCB locally drops less than −70°C and a typical formation pattern of the back-building type (Bluestein and Jain 1985) is also observed in the QSCB (Fig. S4a in Supplement).

In 2020NK, both upper-level and middle-level troughs exist over China, and Kyushu is located in the south of the subtropical jet stream (Figs. 3a and 3b). A very moist airflow from the west and a moist airflow along the edge of the Pacific high from the southwest merge in Kyushu in the south of the Baiu front (Fig. 3c). Two mesoscale BFDs are also found and a QSCB is located in the convergence zone associated with the inflow that has significantly large low-level water vapor flux (Fig. 3d). Upper-level clouds almost cover Kyushu, and the CTT of the QSCB also locally drops −70°C (Fig. S4b in Supplement).

These results indicate that the environmental occurrence conditions for QSCBs in 2020KK and 2020NK are strongly associated with mesoscale BFDs. Environmental fields of QSCBs in 2018NK and 2017NK are also shown in Figs. S5 and S6 in Supplement, respectively. In 2018NK, a clear convergence line associated with large low-level water vapor flux is also found near the Baiu front, and a QSCB forms along the convergence line (Fig. S5). A QSCB forms in a low-level convergence zone in 2017NK, as shown by Kawano and Kawamura (2020), but the low-level water vapor flux is considerably smaller than that in the other cases because horizontal wind in the inflow along the edge of the Pacific high is weaker in addition to smaller water vapor amounts (Fig. S6). It should be noted that no apparent mesoscale BFD is found both in the 2018NK and 2017NK.
3.3 Characteristics of atmospheric environments of QSCBs

To quantitatively characterize the environmental occurrence conditions for extreme rainfall events, environmental parameters for each period of 2020KK, 2020NK, 2018NK, and 2017NK are compared (Table 2). As for observational features, CTT and CTH in 2020KK are the lowest and the highest in comparison with the other events, respectively. FLASH in 2020KK temporally exceeds 1400 times h⁻¹, which is higher than the period-averaged FLASH in 2017NK. These results show that the QSCB in 2020KK was composed of very tall and thunderous cumulonimbus clouds among the recent extreme rainfall cases.

Regarding the features of upper-level and middle-level temperature fields, T250 is lower in 2017NK and 2020KK, and significant cold air advection at 250 hPa is found in 2020KK. T500 is the highest in 2020KK and the lowest in 2017NK, and significant warm air advection is found at 500 hPa in 2020KK. Concerning the features of water vapor fields, PWV in 2020KK is more than 77 mm, which is comparable to that in 2018NK as noted as an extremely large value by Takemi and Unuma (2019). WV950 is almost the same values in each event, but VEL950 is larger in 2020KK and 2020NK, resulting in extremely large FLWV950 over 530 g m⁻² s⁻¹. In terms of thermodynamic stability, CAPE is 1678 J kg⁻¹ in 2020KK, which indicates an extremely unstable atmospheric condition. LNB is also 100 hPa throughout the period only in 2020KK, indicating the thermodynamic environments favorable for deep convection development. Regarding aspects of dynamic environments, SREH in each event is more than 100 m² s⁻² and satisfy the conditions favorable for QSCB formation (Kato 2020). W700 in 2020KK is larger than that in 2018NK where the environment was significantly affected by synoptic-scale ascent (e.g., Takemura et al. 2019).

To understand the relationship between environmental parameters and precipitation amounts in case of QSCB, scatter diagrams of environmental parameters for R1max are also examined (Fig. S7 in Supplement). Parameters of FLWV950, PWV, CAPE, and W700 tend to increase with R1max, except in the 2017 event (Figs. S7a, S7b, S7c, and S7d). CTT tends to become lower as R1max increases, and most of QSCB cases have CTT below −65°C, with the lowest CTT observed in 2020KK (Fig. S7e). A clear relationship with the precipitation amount is not found for FLASH (Fig. S7f), and the other environmental parameters in Table 2 (not shown). Focusing on the environmental parameters for QSCBs, FLWV950 is over 450 g m⁻² s⁻¹ during all the appearance periods of QSCBs in the 2020 event (Fig. S7a). These results indicate that all the QSCBs in the 2020 event were composed of very tall cumulonimbus clouds and formed under the environmental conditions with extremely large low-level water vapor flux. It should be noted that these results were not significantly different when environmental parameters estimated from 1 or 2 hours prior to the time of R1max were used.
Present analyses based on case studies and environmental parameters show that the environmental fields in 2020KK are characterized by upper-level cold air, middle-level warm air, synoptic-scale ascent, and extremely large PWV and low-level water vapor flux. To investigate the environmental occurrence conditions for QSCBs under the influence of mesoscale BFDs as described in Ogura et al. (1985), vertical profiles of T, WV, VEL, and FLWV for 2020KK, 2020NK, 2018NK, and 2017NK are shown in Fig. 4. The average is obtained from hourly LA data of 1−10 July in 2015−2020 in the domain of the broken rectangle in Fig. 2d.

In 2020KK, a negative anomaly of T is also found in the upper-level layer from 300 to 150 hPa, and T and WV are larger than the averaged values from the low-level to middle-level layers, with the largest anomalies at 500 and 700 hPa, respectively (Figs. 4a and 4b). Although a small positive anomaly (~0.6 g kg\(^{-1}\)) is found in WV\(_{950}\) for each event, the difference of the middle-level WV would be responsible for that of PWV. From this result, it is noted that the upper-level cold airflow in the environmental conditions with extremely large PWV due to low-level and middle-level humidity enhances the atmospheric unstable condition favorable for the development of deep convection, which could result in higher lightning activity and the highest cloud top height among the present heavy rainfall events.

The environmental fields in 2020KK and 2020NK are also characterized by stronger winds at all levels than those in 2017NK and 2018NK (Fig. 4c), resulting in extremely large FLWV in a low-level atmosphere (Fig. 4d). Especially in 2020KK, the peak of horizontal velocity is found at approximately 900 hPa, which is a similar feature of moist low-level jets in the environmental occurrence conditions for heavy rainfall associated with mesoscale BFDs (e.g., Ogura et al. 1985). The results of the case studies indicate that QSCBs formed along a convergence line/zone associated with BFDs, which played an important role in the intensification of very moist low-level inflows in 2020KK and 2020NK. All of the QSCBs in the 2020 event form when FLWV\(_{950}\) becomes extremely large (Fig. S7a), and the intensification of FLWV\(_{950}\) is caused by mesoscale BFDs, which have got apparent from a few hours to a day before the formation of QSCBs, in eight of nine

### Table 2. Environmental parameters averaged for each heavy rainfall period of 2020KK, 2020NK, 2018NK, and 2017NK.

| Parameter | Unit | Value in domain |
|-----------|------|-----------------|
| R\(_{1\text{max}}\) (Total) | mm h\(^{-1}\) (mm) | Max 140 (683) 110 (590) 90 (303) 180 (957) |
| CTT (Min) | °C | Min -78.3 (-80.3) -71.2 (-76.9) -72.0 (-73.4) -69.0 (-73.4) |
| CTH (Max) | km | Max 16.8 (17.8) 16.4 (17.2) 16.1 (16.7) 16.2 (16.8) |
| FLASH (Max) | times h\(^{-1}\) | - 269 (1443) 38 (128) 0.4 (5) 1288 (2279) |
| \(T_{270}\) | °C | Ave -38.4 -36.8 -36.3 -40.3 |
| \(T_{300}\) | °C | Ave -2.6 -3.8 -3.3 -6.0 |
| TADV\(_{50}\) | °C h\(^{-1}\) | Ave -0.32 0.02 -0.06 -0.07 |
| TADV\(_{60}\) | °C h\(^{-1}\) | Ave 0.28 0.02 0.00 -0.18 |
| PWV | mm | Max 77.4 73.2 77.1 64.0 |
| WV\(_{950}\) | g kg\(^{-1}\) | Max 19.3 19.0 19.2 18.9 |
| VEL\(_{950}\) | m s\(^{-1}\) | Max 27.8 26.1 22.2 13.7 |
| FLWV\(_{950}\) | g m\(^{-2}\) s\(^{-1}\) | Max 582 538 462 231 |
| CAPE | J kg\(^{-1}\) | Max 1678 1354 1073 2184 |
| LNB | hPa | Min 100 120 105 148 |
| SREH | m\(^2\) s\(^{-2}\) (Ave 100km) | Max 370 390 265 136 |
| W\(_{700}\) | m s\(^{-1}\) (Ave 400km) | Ave 0.055 0.038 0.042 0.024 |

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Fig. 4. Vertical profiles of difference of (a) temperature (T), (b) mixing ratio of water vapor (WV), (c) horizontal velocity (VEL), and (d) water vapor flux (FLWV) from average (AVE). The AVE is obtained from hourly local analysis data of 1−10 July in 2015−2020 in the domain of the broken rectangle in Fig. 2d. Profiles of 2020KK are calculated in the domain of 127.5°E−130.0°E and 30.5°N−32.5°N, and those of 2020NK, 2018NK, and 2017NK are shown in Fig. 4. The average is obtained from hourly LA data of 1−10 July in 2015−2020 in the domain of the broken rectangle in Fig. 2d.

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**Table 2.** Environmental parameters averaged for each heavy rainfall period of 2020KK, 2020NK, 2018NK, and 2017NK. Total, Max, and Min in parentheses in a column of parameters and each event show the total, maximum, and minimum values for the period, respectively. Only the maximum hourly precipitation amount (R\(_{1\text{max}}\)) shows the maximum value for the period. Parameters with Max, Min, and Ave in the "Value in domain" column represent the maximum, minimum, and averaged values for the domains of 127.5°E−130.0°E and 30.5°N−32.5°N for 2020KK, and 127.5°E−130.0°E and 31.5°N−33.5°N for 2020NK, 2018NK, and 2017NK, respectively.
QSCB cases (Fig. 5). The enhancement of precipitation associated with the very moist low-level inflow around the mesoscale BFDs that was found not only in 2020KK and 2020NK but also in most of the 2020 QSCB cases was also ascertained in the Nagasaki heavy rainfall event on 23 July 1982 (Ogura et al. 1985). On the other hand, in all the 2018 QSCB cases, any mesoscale BFDs are not apparent, and the QSCBs are located along the low-level convergence lines associated with large FLWV at 950 hPa that is smaller compared to the 2020 QSCB cases because of weaker horizontal winds (Fig. S8 in Supplement).

Since the low-level water vapor field is important for the initiation of moist convection leading to heavy rainfall as shown by Kato (2018), extremely large low-level FLWV could play an important role in the occurrence of short-term heavy rainfall during the 2020 QSCB cases. As heavy rainfall occurred mainly on land, topography could also affect on precipitation enhancement, as noted in previous studies (e.g., Yoshizaki et al. 2000; Takemi 2018). To understand the formation and maintenance processes of QSCBs, detailed analyses on the role of mesoscale depressions and convergence lines/zones using observation data are required, which is in our future works.

4. Conclusion and remarks

In this study, the characteristics of environmental fields in the occurrence of QSCBs in Kyushu during the July 2020 heavy rainfall event were investigated and compared with those in the 2018 and 2017 heavy rainfall events. Nine QSCBs were observed during the 2020 event, causing short-term heavy rainfall with 20 times exceeding 100 mm h⁻¹. The number of QSCBs and occurrence rate of short-term heavy rainfall caused by QSCBs...
in the 2020 event were significantly higher than those in the 2017 and 2018 events.

In 2020KK, environmental fields were characterized by extremely large PWV due to low-level and middle-level humidity and upper-level cold airflow, which resulted in the enhancement of atmospheric unstable conditions favorable for the development of deep convection. It is noted that the environmental conditions in 2020KK had the hybrid characteristics of extremely large PWV and strong synoptic-scale ascent as in 2018NK and upper-level cold air as in 2017NK. Consequently, the lightning activity was high in 2020KK and cloud top heights of QSCBs were the highest compared to those in 2018NK and 2017NK.

QSCBs in 2020KK and 2020NK were located along a low-level convergence line/zone associated with inflows with extremely large low-level water vapor flux on the south side of mesoscale BFDs. Although the QSCBs in 2018NK and 2017NK were also located along low-level convergence lines/zones, environmental fields in 2020KK and 2020NK were different from those in 2018NK and 2017NK in respect to the existence of mesoscale BFDs and extremely large low-level water vapor flux amounts. Mesoscale BFDs were apparent and intensified horizontal winds in most of the QSCB cases in 2020, causing extremely large low-level water vapor flux, which resulted in short-term heavy rainfall. The features of environmental conditions with mesoscale BFDs and moist low-level inflows found in 2020KK and 2020NK were also ascertained in the Nagasaki heavy rainfall event on 23 July 1982.

Our results suggest that monitoring and predicting mesoscale BFDs, in addition to the low-level water vapor field, could potentially improve the forecast of QSCBs causing short-term heavy rainfall. Further accumulation of case studies and numerical studies with advanced data assimilation and physical processes are desired. These are our future issues.

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Supplement

Supplement: Figures showing occurrence distribution, environmental occurrence conditions, cloud top temperature of QSCBs, and comparison between the LA and radiosonde data. Precipitation data is partially derived from the GSMaP (Kubota et al. 2020).

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