Characteristics of the Environmental Conditions for the Occurrence of Recent Extreme Rainfall Events in Northern Kyushu, Japan

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Abstract Using mesoscale gridded analysis data and radar/raingauge-analyzed precipitation products, this study investigated the environmental conditions for the occurrence of extremely heavy rain events that occurred in northern Kyushu during the warm season in recent years. In all cases, the environmental conditions were not particularly unstable but were almost saturated in the deep layer of the troposphere. The existence of moist absolutely unstable layers (MAULs) was confirmed in and around the rainfall areas. A positive correlation was found between the volume of deep MAULs and the area total rainfall. A large convergence of the water vapor flux is observed in the lower troposphere, which appears to maintain very humid conditions and MAULs. The moisture convergence in the lower troposphere and the presence of deep MAULs is considered to enhance the heavy rainfall in the preceding hours. Humid conditions form deep MAULs that appear to precede the heavy rainfalls.

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1. Introduction

During the Baiu season in Japan, heavy rainfalls frequently occur and sometimes cause substantial damage to society. For example, severe disasters have occurred in the last several years because of heavy rainfall in northern Kyushu in July 2017 (Kato et al. 2018; Takemi 2018), heavy rainfall in July 2018 (Tsuguti et al. 2018), Typhoon Hagibis in 2019 (Takemi and Unuma 2020), and heavy rainfall in July 2020 (Hirockawa et al. 2020; Tochimoto et al. 2022). It was found that such recent heavy rainfalls are associated with the transport of a large amount of water vapor (Shimpo et al. 2019; Sekizawa et al. 2019; Takemura et al. 2019). As found for quasi-stationary convective clusters (QSCCs) during the warm season in Japan (Unuma and Takemi 2016), the environment for such heavy rain–producing systems is characterized by the presence of a large amount of water vapor.

Of course, the presence of sufficient moisture does not necessarily lead to heavy rainfall; convective instability and mechanisms for the development of precipitating systems are also necessary. Unuma and Takemi (2016) showed that the temperature lapse rate for QSCC cases is close to the moist adiabatic lapse rate. For example, in the heavy rainfall associated with Typhoon Hagibis in 2019, Takemi and Unuma (2020) pointed out the existence of moist absolutely unstable layers (MAULs) that have a relative humidity (RH) of 100% and a temperature lapse rate greater than the moist adiabatic lapse rate (Bryan and Fritch 2000). In rainy seasons such as the Baiu season, the troposphere is very humid and often approaches 100% RH, especially at low-to-middle levels; therefore, a MAUL is expected to exist when the environment becomes unstable. In fact, Tsuji et al. (2021) showed that the existence of a MAUL in the middle troposphere was closely related to the occurrence of heavy rainfalls in the Kyushu region during the warm season. Thus, the effect of MAULs on the occurrence of heavy rainfall is considered to be an important condition for understanding the mechanism of heavy rainfall during the Baiu season.

Although numerous studies of recent heavy rain events during the Baiu season have been reported (Takemi and Unuma 2019; Araki et al. 2021; Tsuji et al. 2020; Hirockawa et al. 2020), the relationship between MAULs and precipitation has not been quantitatively demonstrated. Therefore, the present study focuses on the moisture content, relative humidity, and the existence of a MAUL as possible environmental conditions for the generation of heavy rainfall events that occurred in northern Kyushu, Japan over the past several years. The northern Kyushu region is chosen here because the environmental conditions for the occurrence of precipitation have regional characteristics (Unuma and Takemi 2016). The purposes of the present study are to investigate the characteristics of the environmental conditions for the occurrence of recent extreme rainfall events and to elucidate the common conditions for the occurrence of heavy rain.

2. Data used and analysis method

The present study uses atmospheric and precipitation data generated by the Japan Meteorological Agency (JMA). For the atmospheric data, we use the initial analysis fields from the operational Mesoscale Model (MSM) that have a

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grid interval of 5 km and a time interval of 3 h. For the precipitation data, the radar/raingauge-analyzed precipitation products (Nagata 2011) having a 1 km spatial resolution and a 1 h interval are used.

To diagnose the environmental conditions for heavy rain, we examine the convective available potential energy (CAPE), precipitable water (PW), temperature lapse rate between 850 and 500 hPa (TLR; Takemi 2007a, 2007b, 2010; Unuma and Takemi 2016), RH, presence of a MAUL (Bryan and Fritsch 2000), and the divergence of water vapor fluxes, as used by Bluestein and Jain (1985), Chuda and Niino (2005), Nomura and Takemi (2011), and Takemi (2014). The CAPE was calculated by adiabatically lifting the air parcel at the ground surface.

A MAUL was identified as an important ingredient in mesoscale convective systems by Bryan and Fritsch (2000). In the present study, following the definition of Takemi and Unuma (2020), we define the MAUL condition as

$$\frac{\partial \theta_e}{\partial z} < 0 \quad \text{and} \quad \mathrm{RH} \geq 99\%, \tag{1}$$

where θ_e is the equivalent potential temperature. Bryan and Fritsch (2000) determined a saturation condition as having a dewpoint depression of less than 1°C; this condition actually corresponds to an RH of approximately 88–94% at the temperatures associated with heavy rainfall events during the Baiu season in Japan. Therefore, the criteria for a MAUL in the present study are stricter than those used by Bryan and Fritsch (2000).

In the present study, four cases of heavy rainfalls that occurred in the northern part of Kyushu in July 2017, July 2018, July 2020, and August 2021 were investigated. The time refers to Japan Standard Time (JST, UTC + 9 h). Figure 1 shows the distribution of the total rainfall during 3 days in Kyushu, as computed from the analyzed rainfall data for each case. In all cases, precipitation exceeding 500 mm was analyzed in northern Kyushu. In the 2017 case, the duration of rainfall was about half a day, while the three-hour cumulative rainfall exceeded 200 mm. In contrast, the 2018 event indicated several peaks of rainfall over 2–3 days. In the 2020 case, heavy rainfalls continued during two days, sometimes exceeding a total amount of 100 mm in a three-hour period during the two days. The 2021 case had continued rainfall from 11 to 15 August, with an three-hourly accumulated amount exceeding 60 mm at some times. Such temporal changes of rainfall can be seen in Supplement 1, which shows the time-series of the three-hour accumulated precipitation at the points marked with white marks in Fig. 1. The environmental conditions associated with these heavy rain events are investigated.

3. Results

From the distribution of the total rainfall shown in Fig. 1, the August 2021 case indicates the widest area of the rainfall exceeding 500 mm. Thus, we first investigate the environmental properties during the heavy rain in August 2021 as an example.

Figure 2 shows the horizontal distribution of the daily mean CAPE and precipitable water in the Kyushu region and its surrounding areas on 14 August 2021 to demonstrate overall features of instability and moisture conditions. This day was chosen because the 2021 case experienced the highest daily precipitation during the time shown in Supplement Fig. 1. The CAPE shows a value of 800 J kg^{-1} or less within areas of rainfall exceeding 200 mm; at Fukuoka, the CAPE is 162.5 J kg^{-1} (Fig. 2a), which is actually smaller than the warm-season means value in Fukuoka for quasi-stationary precipitation systems (Unuma and Takemi 2016). In the southwest direction from this rainfall area, the CAPE values are greater than 1000 J kg^{-1} and increase toward the south; these higher CAPE values are located in the upstream of the heavy rainfall area and are regarded as an environment for the rainfall. The environmental CAPE values appear to be comparable to those observed in the heavy rainfall event in July 2018 (Takemi and Unuma 2019) and are therefore not particularly extreme.

Precipitable water is extremely high, exceeding 70 mm, over the oceanic region to the west of Kyushu (Fig. 2b), which is much larger than the climatological value reported by Unuma and Takemi (2016) for Fukuoka during the development of quasi-stationary precipitation systems. This precipitable water content is comparable to the value observed in the July 2018 heavy rainfall event (Takemi and Unuma 2019) and also in Typhoon Hagibis (2019) (Takemi and Unuma 2020). Thus, the July 2021 case also indicates a large amount of water vapor available for the rainfall.

We next investigate the atmospheric fields over a wider area that includes the Kyushu region. After we examined all the indices listed in Section 2 for all cases, we found that in general the degree of atmospheric instability was not particularly high, whereas the troposphere was in a very humid state (not shown). Therefore, we present here the TLR and RH in the lower and upper troposphere in the case of 2021 in the same way as Figs. 1 and 2. Figure 3 shows the mean TLR and RH averaged on 14 August 2021. The TLR values over and around the Japanese islands are 4.0–5.5 (K km^{-1}) (Fig. 3a). The TLR values in the northern part of Kyushu are 4.5–5.0 (K km^{-1}), whereas those to the southwest of Kyushu are greater than 5 K km^{-1}, consistent with a larger CAPE in the region. These TLR values are slightly lower than the climatological value reported by Unuma and Takemi (2016). The RH averaged in the 1000–700 hPa layer exceeds 90% throughout most of the Japanese islands (Fig. 3b); in the middle and upper layers (i.e., averaged in the

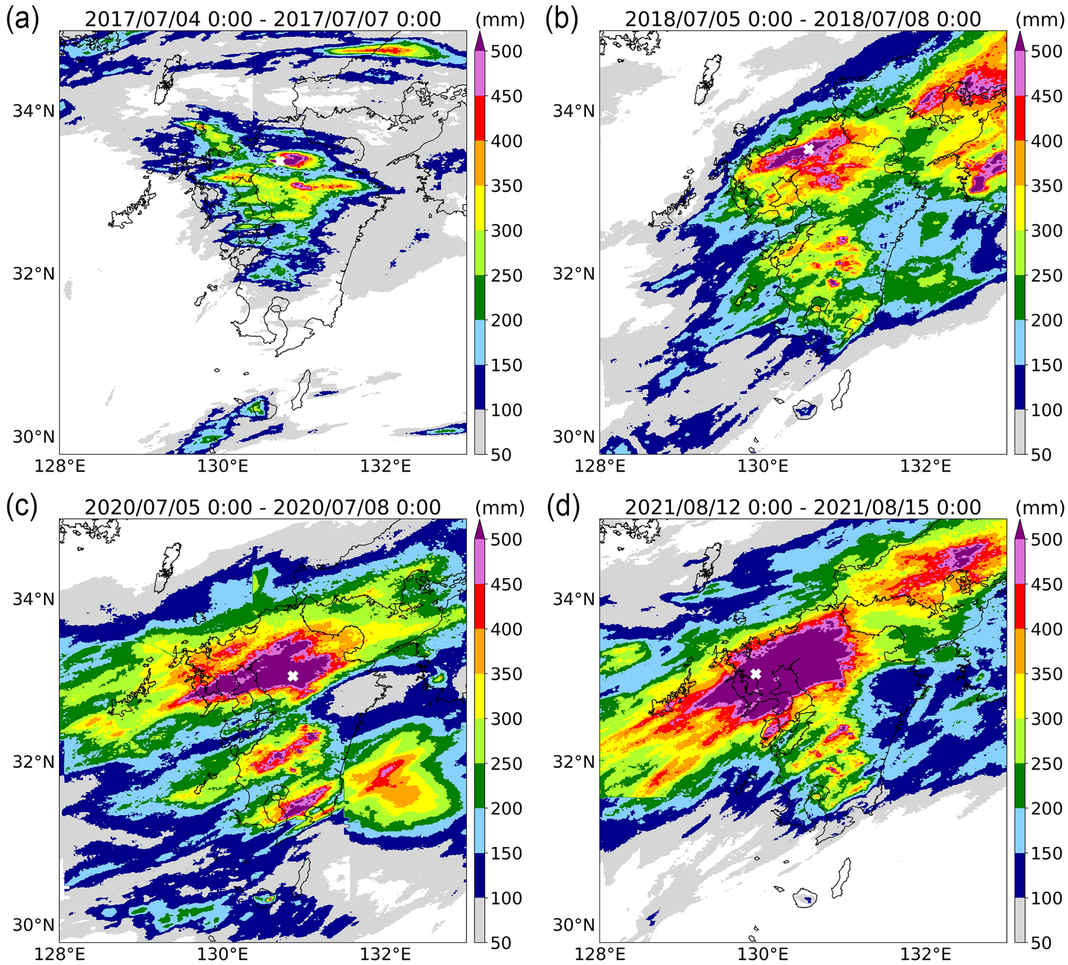

Fig. 1. The horizontal distribution of 3 day total rainfall from radar/raingauge-analyzed precipitation products in the Kyushu area and its vicinity (a) from 0000 JST 4 to 0000 JST 7 July in 2017, (b) from 0000 JST 5 to 0000 JST 8 July in 2018, (c) from 0000 JST 5 to 0000 JST 8 July in 2020, and (d) from 0000 JST 12 to 0000 JST 15 August in 2021. The points marked with white marks denote the location at which the total amount of precipitation during three days in each case was the largest.

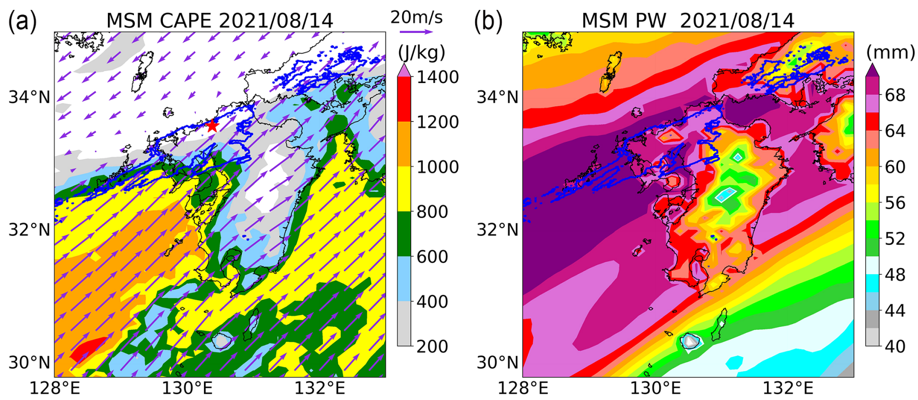

Fig. 2. The horizontal distribution of the daily mean (a) CAPE (in J kg^{-1}, color shading) and (b) precipitable water (PW) (in mm, color shading) averaged on 14 August 2021. The blue lines indicate the contours of the accumulated rainfall of 200 mm on the day. The violet vectors in (a) denote the daily mean wind vectors averaged vertically from 1000 to 700 hPa (the unit vector having a magnitude of 20 m s^{-1} is shown in the upper-right corner). The red star mark in (a) show the location of Fukuoka.

700–300 hPa layer), the RH exceeds 80% throughout the Japanese islands (except in the northern region) and exceeds 90% in some areas. In the northern part of Kyushu, in particular, both the lower and upper middle layers exhibit a very high RH of 90% or greater. Such a RH in the middle-to-upper levels is much higher than in other cases, such as in the 2020 case, where the RH was 80–90%, thereby indicating that all the layers in the troposphere in the 2021 case were extremely wet.

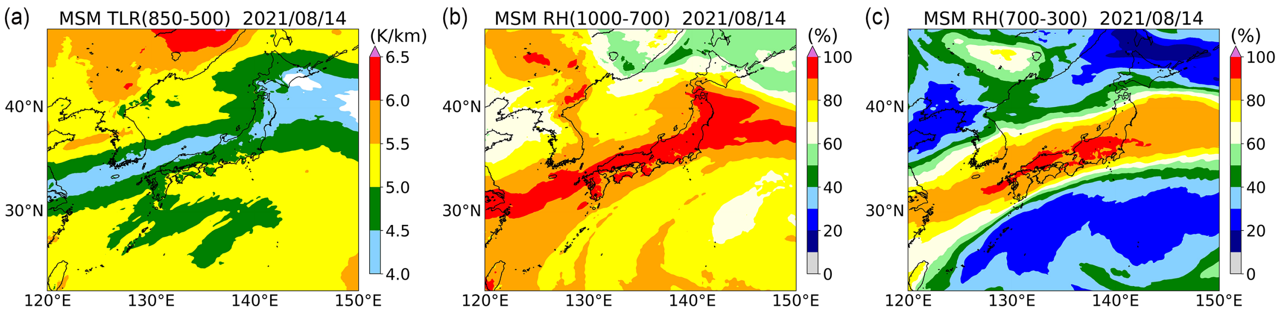

Fig. 3. The horizontal distribution of the daily mean (a) temperature lapse rate in the 850 hPa layer (TLR) (in K km^{-1}), (b) vertically averaged relative humidity in the 1000–700 hPa layer (in %), and (c) vertically averaged relative humidity in the 700–300 hPa layer, averaged on 14 August 2021.

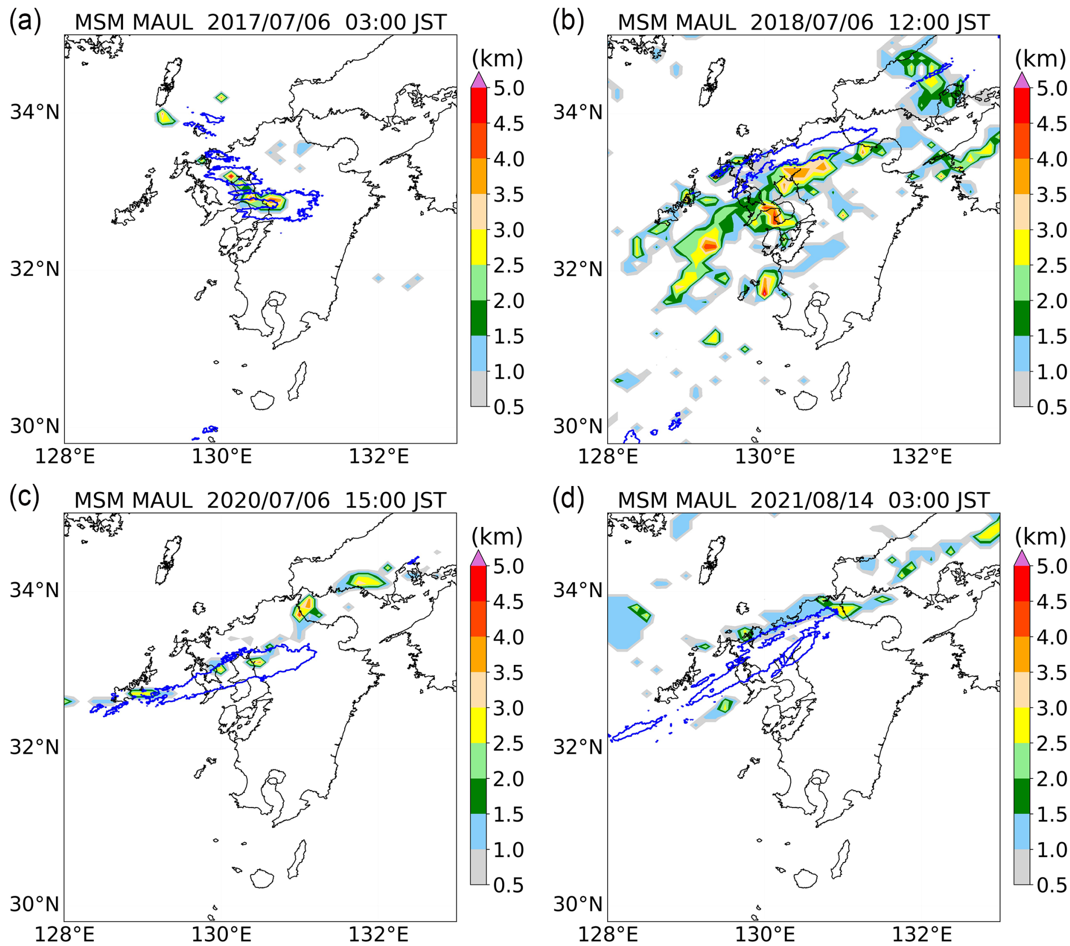

Fig. 4. The horizontal distribution of the thickness of the MAUL (in km, color shading) and the accumulated rainfall of 60 mm for the 3 h afterward (blue contour) in the area around Kyushu at (a) 0300 JST 6 July 2017, (b) 1200 JST 6 July 2018, (c) 1500 JST 6 July 2020, and (d) 0300 JST 14 August 2021.

In summary, the 2021 case shows that the CAPE and TLR are similar to the mean values, whereas precipitable water content and RH are in their higher ranges. The characteristics of the environmental conditions observed in the August 2021 case were identified in the other cases examined in the present study. Because the RH was extremely high and the TLR was 4.5–5.0 K km^{-1}, which is close to the moist neutral state, the presence of a MAUL is expected in the four cases, which will be examined in the following discussion.

As in the study of Takemi and Unuma (2020), the thickness of a MAUL in the present study is examined (Fig. 4) at the indicated time for each case, along with the contour of 60 mm of the accumulated rainfall for the 3 h after the indicated time. The thickness of MAUL is defined as continuous vertical layers that satisfy the Eq. (1). The times shown in Fig. 4 were determined at those when the positional relationship between the rainfall area and MAUL was clearly seen after examining the relationships at other times. In all the cases, deep MAULs with a thickness of 2 km or deeper appear in or near areas with a rainfall exceeding 60 mm for the following 3 h. The areas of deep MAULs appear to be more concentrated than areas with a higher CAPE, greater precipitable water content, larger TLR, and higher RH (not shown) and appear to correspond well with the areas with a large amount of rainfall, as compared with the other environmental indices. When compared among the cases, deep MAULs appear within the heavy rainfall areas in the 2017 and 2020 cases, whereas deeper MAULs appear adjacent to the heavy rainfall areas in the 2018 and 2021 cases.

To quantitatively investigate how MAULs and rainfall are related to each other, Fig. 5 shows the relationship between the total three-dimensional volume of a MAUL having a thickness of 1.5 km or greater and the total amount of 3-hourly rainfall. The MAUL volume is calculated by multiplying the MAUL thickness by the area of MAUL having a thickness of 1.5 km or greater. Both the MAUL volume and the total rainfall amount are computed in the region of 32°N–34°N and 128.5°E–131.5°E. The examined time periods are from 0000 JST 5 to 2100 JST 6 July in 2017, from 0000 JST 28 June to 2100 JST 8 July in 2018, from 0000 JST 3 to 2100 JST 10 July in 2020, and from 0000 JST 10 to 2100 JST 18 August in 2021. The time periods shown in Fig. 5 were determined to cover extended times from the beginning to the end of the precipitation events. The thickness of 1.5 km was chosen after we examined thickness thresholds of 0.5, 1.0, 1.5, and 2.0 km and found that the relationship is more clearly observed for the thickness of 1.5 km. Overall, the increase in the total rainfall amount is positively correlated with the increase in the MAUL volume. Also, in this paper, a MAUL with a thickness of 1.5 km or more is defined as a deep MAUL. The correlation coefficients are 0.685, 0.767, 0.668, and 0.455 for the 2017, 2018, 2020, and 2021 cases, and 0.428 for all cases combined, respectively, confirming positive relationships between the existence of a deep MAUL and a heavy rainfall amount.

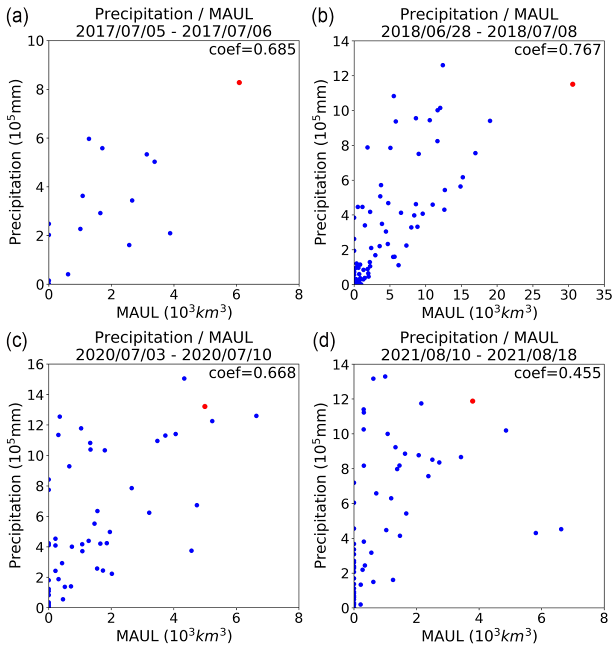

Fig. 5. The scatter plot of the total three-dimensional volume of the MAUL having a thickness of 1.5 km or greater and the total amount of 3-hourly rainfall within the region of 32°N–34°N and 128.5°E–131.5°E, obtained (a) from 0000 JST 5 to 2100 JST 6 July in 2017, (b) from 0000 JST 28 June to 2100 JST 8 July in 2018, (c) from 0000 JST 3 to 2100 JST 10 July in 2020, and (d) from 0000 JST 10 to 2100 JST 18 August in 2021. Scatter plots were drawn using data for 16 times in 2017, 88 times in 2018, and 64 times in 2020 and 2021. The red point in each panel denotes the sample at the time shown in Fig. 4. The correlation coefficient (coef) in each case is indicated in the upper-right corner of each panel.

A MAUL is an absolutely unstable layer and is therefore considered to be quickly stabilized by convective activity. However, a MAUL appears to be maintained for long periods of time during heavy rainfall. Given the fact that the troposphere, especially in the low-to-middle layers, remains almost saturated, which is one of the conditions for a MAUL, the continuous supply of water vapor should play a role in keeping the atmosphere moist.

Figure 6 shows the spatial distribution of the divergence of water vapor flux in the 1000–700 hPa layer and in the area where the total rainfall was 60 mm or greater for 3 h after the indicated time in each case. Substantial moisture flux convergence appears in the vicinity of the heavy rainfall area and is commonly observed in the four cases. Notably, in the 2017 case, the moisture flux convergence occurs in a more concentrated area than in the other cases, which appears to correspond to the deeper MAUL within the heavy rainfall region in the 2017 case (Fig. 4a).

To diagnose the temporal relationships among the MAUL, water vapor transport, and rainfall, we plotted the time series of the area size of the deeper MAUL, the amount of water vapor flux divergence in the 1000–700 hPa layer, and the total amount of rainfall accumulated over the area having rainfall for 3 h afterward (Fig. 7). The time periods shown in Fig. 7 were determined for the same reasons as in Fig. 5. The quantities here were computed for the area of 32°N–34°N and 128.5°E–131.5°E, as in Fig. 5. The water vapor flux convergence and the deeper MAUL are shown to vary in time similarly with each other, showing peaks at similar times; the cross-correlation coefficients are 0.647, 0.681, 0.634, and 0.524 for the 2017, 2018, 2020, and 2021 cases, respectively. The total amount of rainfall also appears to vary in phase with the moisture flux convergence and the deeper MAUL. Because the rainfall here is the accumulated amount until 3 h later, the lower-layer moisture flux convergence and the deeper MAUL precede the rainfall peaks.

4. Summary and discussion

The analysis indicated that the CAPE and temperature lapse rate were not remarkably large compared with the cli-

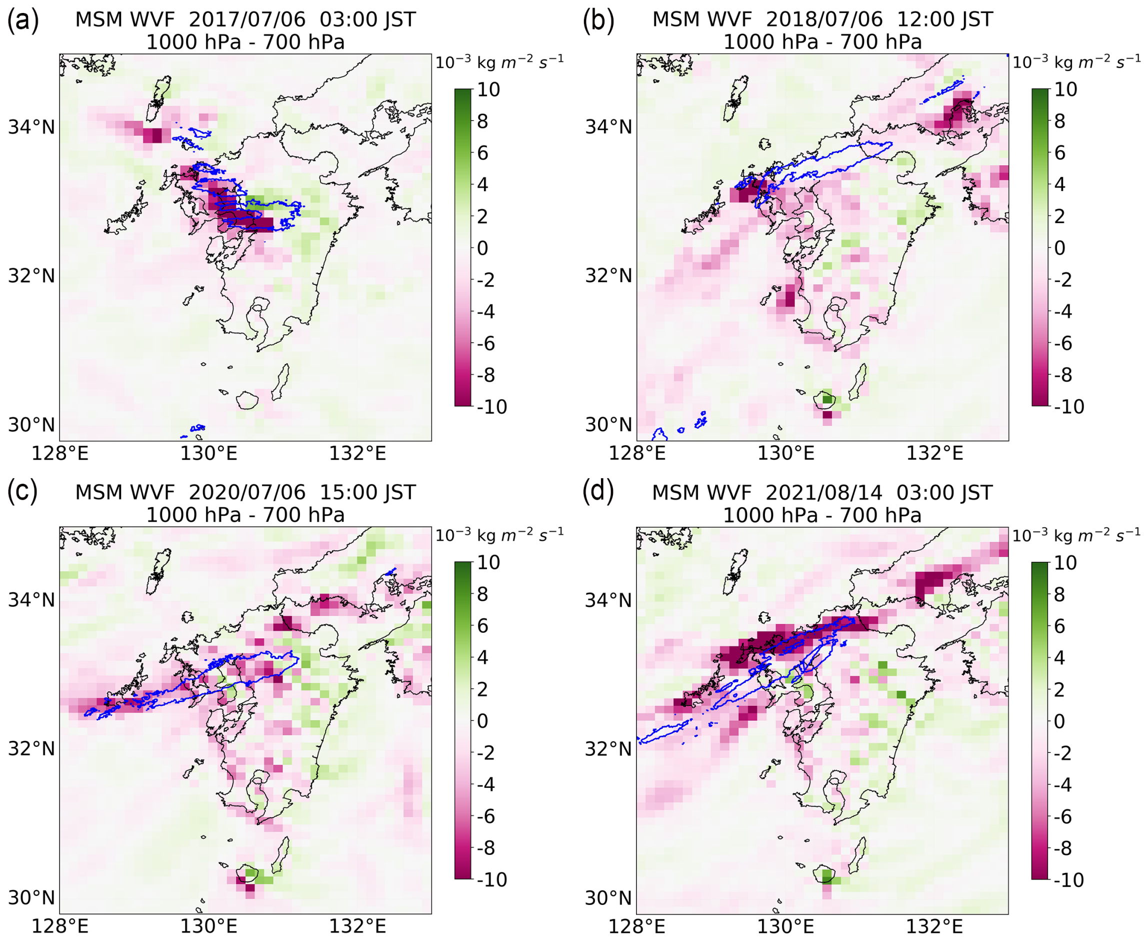

Fig. 6. The same as Fig. 4, except for the divergence of water vapor flux in the 1000–700 hPa layer (color shading, in units of 10^{-3} kg m^{-2} s^{-1}).

matological values for QSCCs. However, the moisture-related parameters such as the precipitable water content and the RH showed very high values. The examined heavy rainfall events in northern Kyushu during the recent warm season were characterized by an extremely large amount of moisture rather than by the degree of atmospheric instability. A similar feature was also observed in the heavy rainfall case of Typhoon Hagibis (2019) (Takemi and Unuma 2020).

Compared with other meteorological conditions, the areas of deep MAULs correspond well with precipitation areas. The total volume size of deeper MAULs in and around the precipitation area is positively correlated with the total amount of rainfall. As observed in the typhoon rainfall case (Takemi and Unuma 2020), the presence of deep MAULs appears to precede heavy rainfall occurrence for the heavy rainfall events in non-typhoon cases. The analysis of temporal changes of the deep MAUL area and the rainfall area supports the time sequence of preceding MAUL existence against the increase of rainfall. The moisture flux convergence was found to maintain the MAUL in and around the rainfall area.

Tsuji et al. (2021) have reported that the vertically integrated water vapor flux convergence increases prior to precipitation and that the depth of a MAUL increases near the peak of precipitation. As demonstrated in the present time-series analysis, the increased moisture convergence and the resultant areal extension of deep MAULs are considered to lead to the increase in the rainfall amount, probably through the increase in rainfall intensity.

5. Conclusions

We investigated the environmental properties of four heavy rain events that occurred in northern Kyushu during the warm season in recent years. Commonly found features are an excessive amount of tropospheric moisture and almost saturated states in the lower-to-middle troposphere, which are considered to be supported by substantial moisture flux convergence in the lower troposphere. Such humid conditions form deep MAULs that appear within limited areas in and around the area of heavy rainfalls and appear to precede the heavy rainfalls.

As a future study, we would investigate the causal relationship between the presence of MAULs and the occurrence of heavy rains. For example, it will be important to investigate the vertical structure of MAUL and moistening process-

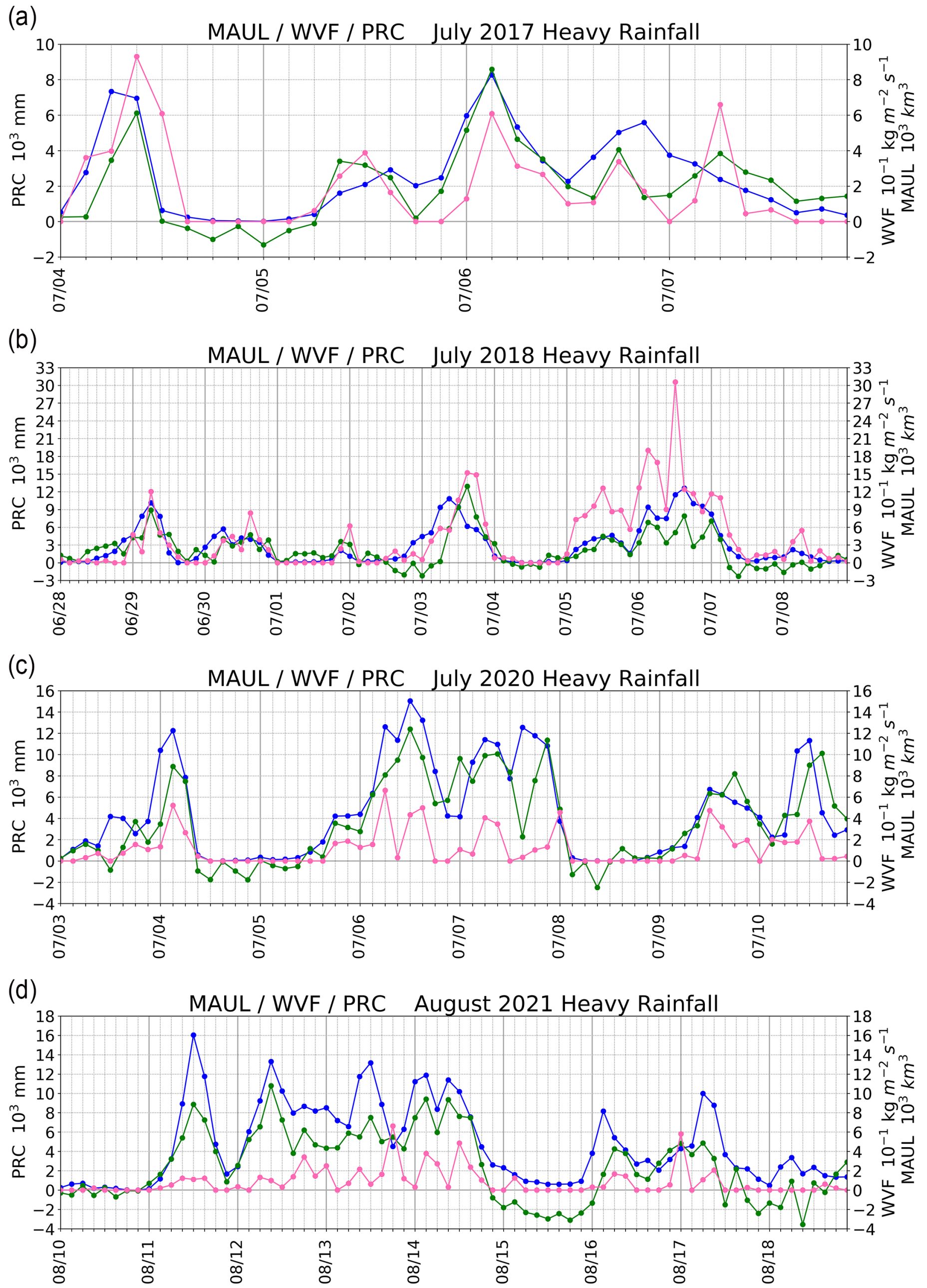

Fig. 7. The time series of the total three-dimensional volume of the MAUL having a thickness of 1.5 km or greater (pink lines), the convergence of the vertically integrated water vapor flux in the 1000–700 hPa layer (WVF, green lines), and the total amount of rainfall (PRC, blue lines) for the next 3 h in the region of 32°N–34°N and 128.5°E–131.5°E (a) from 0000 JST 4 to 2100 JST 7 July in 2017, (b) from 0000 JST 28 June to 2100 JST 8 July in 2018, (c) from 0000 JST 3 to 2100 JST 10 July in 2020, and (d) from 0000 JST 10 to 2100 JST 18 August in 2021.

es that lead to a saturated, unstable condition. Also, the time lag of precipitation with respect to MAUL or the convergence of water vapor flux needs to be investigated in more detail in future studies. For this purpose, statistical analyses with long-term mesoscale analysis datasets are underway.

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Supplement 1

The time-series of the three-hour accumulated precipitation at the points marked with white marks in Fig. 1.

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