Environmental Factors for the Development of Heavy Rainfall in the Eastern Part of Japan during Typhoon Hagibis (2019)

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Abstract

This study investigated the environmental factors responsible for the development of heavy rainfall in eastern Japan during the passage of Typhoon Hagibis (2019) by using mesoscale gridded analysis data as well as observed data. Environmental indices for diagnosing stability and moisture conditions were examined. It was found that the whole troposphere is almost saturated and the column total water vapor content is extremely large. In the lower troposphere we identified layers of moist absolutely unstable states with the thickness deeper than 2 km. Such deep moist absolutely unstable layers as well as abundant moisture content and almost saturated troposphere set a high potential for convective development. Under these favorable environmental conditions, the fact that the heights of the absolutely unstable layers' bottom are comparable to the mountain elevations is considered to be favorable for topographic lifting of unstable, moist air, which will trigger and activate strong convection and hence heavy rainfall. In spite of a moderate amount of convective available potential energy and a nearly moist-adiabatic lapse rate, moist absolute instability, abundant moisture, and high humidity jointly play a key role to increase the potential for generating the present heavy rainfalls.

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1. Introduction

Typhoon Hagibis (2019), which intensified with its lifetime minimum central surface pressure of 915 hPa and made landfall over Japan in October 2019, caused heavy rainfalls and spawned devastating damages in eastern Japan. There were more than 100 dead or missing (Cabinet Office 2019). At the Hakone station, the daily rainfall on 12 October was 922.5 mm, which broke the daily rainfall record in Japan. In contrast to the July 2018 heavy rainfall in central and western Japan, which lasted more than 72 hours (Shimpo et al. 2019), the heavy rainfall by Typhoon Hagibis was mostly concentrated within 24 hours. In other words, this typhoon-induced heavy rainfall is characterized as concentrated rainfall with stronger intensities but shorter duration than found in the July 2018 heavy rainfall. In the past, extremely heavy rainfalls sometimes occurred during the typhoon landfall and/or passage. For example, Typhoon Talas (2011) caused total rainfall of around 2000 mm in Kii Peninsula in Japan (Takemi 2019); Typhoon Morakot (2009) produced extreme rainfall exceeding 3000 mm totally and spawned devastating floodings and landslides in Taiwan (Chien and Kuo 2011); and Typhoon Tokage (2004) caused widespread heavy rainfalls over Japan. In this way, typhoons are major hazards for extreme rainfalls in East Asia. Therefore, meteorological factors that caused the heavy rainfall in October 2019 have to be clarified not only from a scientific point of view but also from a viewpoint of disaster prevention and mitigation.

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From the analyses on recent heavy rainfall events, Tsuji et al. (2020) examined large-scale environments relevant for the heavy rainfall events in Kyushu in July 2017 and in western Japan in July 2018 and found that the environment for the July 2018 case is characterized as having relatively stable and very humid conditions while that for the July 2017 case is more unstable and drier than the July 2018 environment. Takemi and Unuma (2019, hereafter referred to as TU19) demonstrated that the environmental moisture content for the July 2018 case is extremely larger than the climatology of quasi-stationary convective systems (Unuma and Takemi 2016, hereafter referred to as UT16), which is due to very humid conditions not only at lower-levels but also in the middle troposphere. During the Baiu season such moister conditions at the middle-levels are typically found (Kato et al. 2007). It was found in Kato et al. (2007) that the tropospheric temperature lapse rate is around 5.0−5.5, with a larger value for a deeper cumulonimbus. Thus, the vertical profiles of humidity and temperature are of special interest.

This study investigates the environmental factors for the occurrence of heavy rainfalls in eastern Japan during the passage of Typhoon Hagibis. We specifically focus on thermodynamic conditions that contribute to increase the potential for the development of the rainfalls by using mesoscale analysis data.

2. Data and analysis approach

The data used were hourly radar/raingauge analyzed rainfalls (Nagata 2011), sounding data observed at Japan Meteorological Agency (JMA) sites, and three-hourly analysis data from the JMA's Mesoscale Model (MSM). The analyzed rainfall data have 1-km spatial resolution, while the MSM analysis data have 5-km resolution. Only the initial values of the MSM forecasts were used to demonstrate the environmental conditions. In Section 3.2, the validity of the MSM analyses is confirmed against the sounding data.

In previous studies (e.g., Bluestein and Jain 1985; Chuda and Niino 2005; Nomura and Takemi 2011; Takemi 2014; UT16; TU19), thermodynamic stability indices were used to diagnose the environmental potential for convective development. In addition, temperature lapse rate between the levels of 850 hPa and 500 hPa (Takemi 2007a, 2007b, 2010, UT16) was found to be useful for mesoscale analyses. Thus, we initially examined such environmental parameters and, among the parameters, decided to use convective available potential energy (CAPE), precipitable water vapor (PW), temperature lapse rate between the levels of 950 hPa and 500 hPa (TLR), and relative humidity conditions. Note that CAPE was computed by raising an air parcel at the 500-m level with properties averaged in the lowest 500 m depth. In computing TLR, we chose the 950−500 hPa layer instead of the 850−500 hPa layer because the present boundary-layer depth was very shallow and the humid layer extended above the level of around 950 hPa (see Figs. 3d, 3e, and 3f).

Under very humid conditions the temperature lapse rate is generally close to or smaller than the moist-adiabat. However, Bryan and Fritsch (2000) found that there is sometimes a very humid layer with the temperature lapse rate being greater than moist-adiabat, within or nearby mesoscale convective systems (MCSs). Such layers are called as moist absolutely unstable layers

(MAULs), which are absolutely unstable against moist adiabatic conditions. We will also examine whether and how MAULs appeared during the present heavy rainfall.

We referred to the times as Japan Standard Time (JST), which is 9 hours plus UTC. The geographical map including the locations of observation sites is provided in Supplement 2.

3. Results

3.1 Observed features of the rainfall event

Firstly, the rainfall characteristics and their environmental conditions are briefly presented with the use of observation data.

The total amount of rainfall for 5 days including the period of the Typhoon Hagibis landfall is shown in Fig. 1. A large amount of rainfall exceeding 200 mm extends in the eastern part of Japan. During this time period, the maximum amount among observed at surface stations is 1020.5 mm at Hakone, which is about 3 times as large as the October mean and about one third of the annual mean precipitation at that site. There are a large number of surface stations with heavy rainfalls that broke their observed records (JMA 2019).

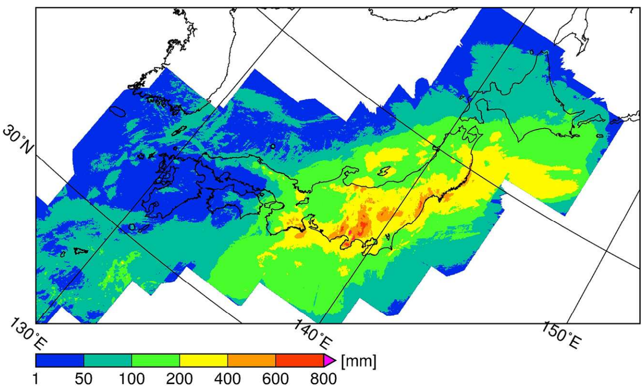

Fig. 1. The accumulated rainfall amount (mm) during the period from 0000 JST 10 October to 2400 JST 14 October 2019.

Figure 2 demonstrates the temporal changes of the spatial patterns of 6-hourly rainfall on 11 and 12 October 2019. It is seen that, with the approach of the typhoon, the rainfall amount over the land regions increases and the area of rainfall exceeding 80 mm becomes widespread. In the afternoon of 12 October, the area of rainfall even greater than 160 mm was spreading.

For the occurrence of these heavy rainfalls, the atmospheric moisture and stability must play a critical role. From sounding data, Fig. 3 exhibits the content and low-level flux of moisture and the stability at 2100 JST 11 October, 0900 JST, and 2100 JST 12 October. PW in eastern Japan are generally much higher than the October climatology (Chuda and Niino 2005) and even higher than the means for quasi-stationary convective systems (UT16). At Tateno, for example, the values are 54.0, 60.6, and 57.4 at the times shown, while the October median values are about 22 in Chuda and Niino (2005) and 39 in UT16. Because of the higher value as well as the typhoon winds, moisture flux at the 925-hPa level is very large at Tateno, which supplies a sufficient amount of moisture towards eastern Japan.

Figures 3d, 3e, and 3f demonstrate that the temperature lapse rates are overall close to moist-adiabats, but also show that there are some layers in which temperature lapse rate exceeds moist-adiabats. In Figs. 3d and 3e, layers with larger lapse rates are seen in the lower troposphere, corresponding to drier conditions. However, a close look at Fig. 3e indicates that there is a saturated layer with the lapse rate larger than moist-adiabat at around 950 to 850-hPa levels, i.e., MAUL. Because of the absolute instability, MAUL indicates a high potential for convective development. In addition, the atmosphere is almost saturated throughout the troposphere. These features of stability and moisture conditions are investigated with the MSM data in the next subsection.

3.2 Mesoscale environmental analysis

Before examining the MSM data, we compared the MSM

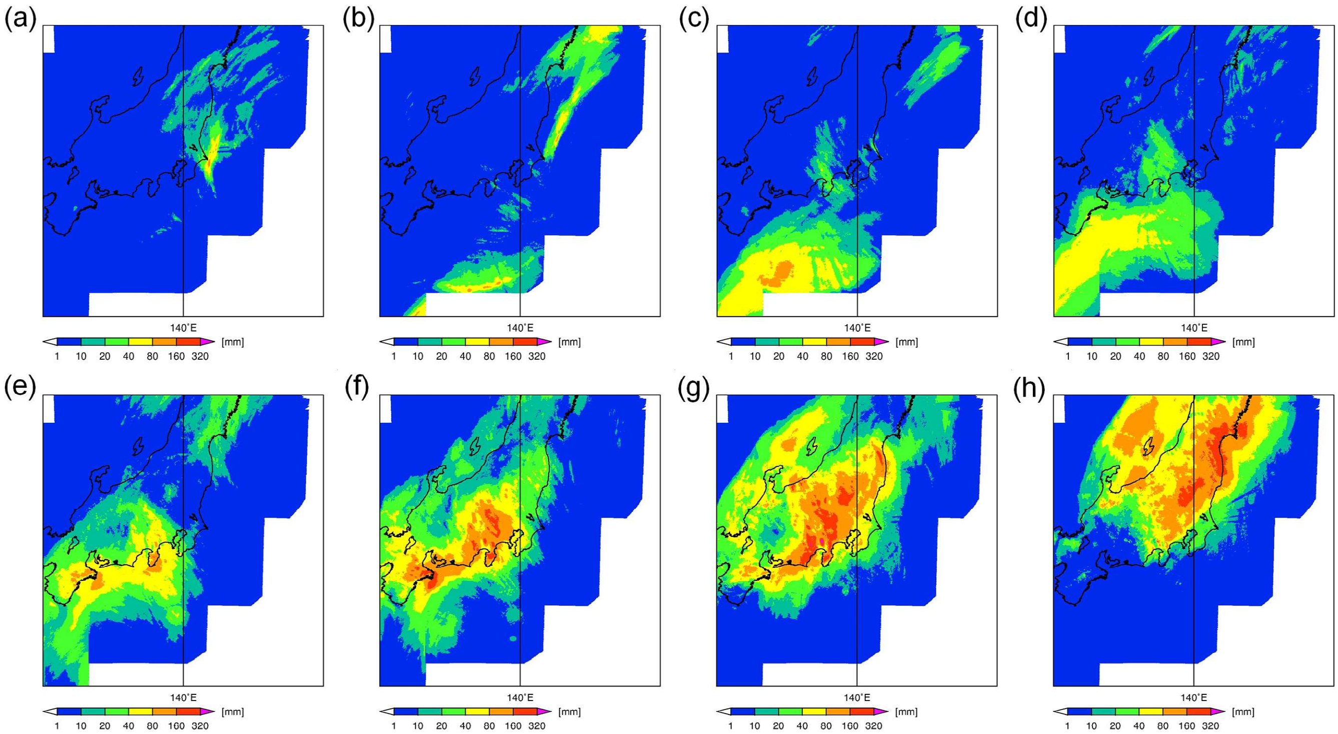

Fig. 2. The distribution of 6-hourly rainfall (mm) on 11 October (during (a) 0000 and 0600 JST, (b) 0600 and 1200 JST, (c) 1200 and 1800 JST, and (d) 1800 and 2400 JST) and 12 October (during (e) 0000 and 0600 JST, (f) 0600 and 1200 JST, (g) 1200 and 1800 JST, and (h) 1800 and 2400 JST).

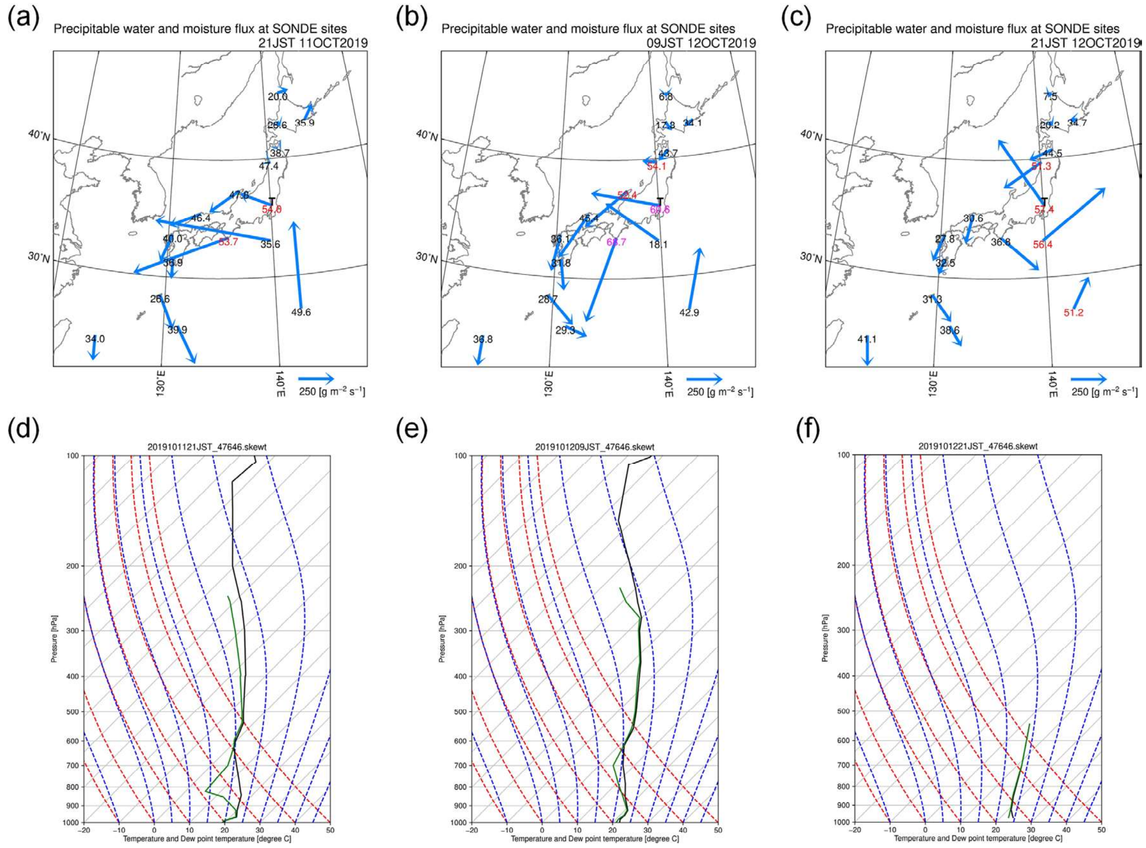

Fig. 3. Precipitable water vapor content (black and color digits, kg m-2) and the horizontal water vapor flux (vector) at the 925-hPa level at (a) 2100 JST 11 October, (b) 0900 JST 12 October, and (c) 2100 JST 12 October 2019, and skew *T*-log *p* diagram at Tateno (WMO location ID: 47646; denoted as T) at (d) 2100 JST 11 October, (e) 0900 JST 12 October, and (f) 2100 JST 12 October 2019. In the skew *T*-log *p* diagram, black and green solid lines indicate observed temperatures and dew-points, respectively, gray solid lines denote constant temperatures, and red and blue dotted lines denote dry and moist adiabats, respectively.

data with the sounding observations. Supplement 1 summarizes the comparison between the MSM and observed data in terms of temperature, relative humidity, and zonal-/meridional-winds at 925, 850, 700, and 500 hPa levels at Wakkanai, Sapporo, Akita, Wajima, Tateno, Matsue, Shionomisaki, Fukuoka, and Kagoshima from 0900 JST 10 October to 2100 JST 14 October 2019. The MSM data are spatially averaged in 100 km^2 areas centered at the sounding sites. The correlation coefficients for temperature mostly exceed 0.9 and those for humidity are generally greater than 0.8, indicating that the MSM data are regarded as representing actual atmospheric conditions, especially over land and the surrounding coastal regions.

Stability and moisture conditions at 0000 and 1200 JST 12 October, when a large amount of rainfall occurred, are demonstrated in Fig. 4. CAPE is at most 800 over eastern Japan and is comparable to that seen in the July 2018 heavy rainfall case (TU19). TLR is larger in eastern Japan than in other regions but is generally below 6, which is not so large as compared to those seen for quasi-stationary convective systems (UT16) and the July 2018 heavy rainfalls (TU19).

In contrast, PW is very high; the PW amounts are greater than 60 over areas where heavy rainfalls occurred. There are even areas with extreme PW amounts exceeding 70, which corresponds to the maximum value seen in the July 2018 heavy rainfalls shown in TU19. Furthermore, near the center of the typhoon PW is greater than 80. Such extreme moisture contents are considered to appear because of very humid conditions as indicated in Fig. 3. Relative humidity at a middle-level (Figs. 4d and 4h) actually exhibits almost saturated conditions that are widespread over eastern Japan.

Humidity conditions are further examined with the mean relative humidity averaged in the layer of 700−300 hPa, as in TU19. Figure 5 shows the vertical-mean relative humidity on 12 October, indicating that there are land regions where the averaged humidity exceeds 90%. With the northward movement of the typhoon, such very humid regions also shift northward. In this way, almost saturated conditions in the troposphere, as indicated by the soundings in Fig. 3, extend widely in eastern Japan.

Middle-level humid conditions are frequently seen in environments for convective rainfalls over Japan (Nomura and Takemi 2011; UT16; Hamada and Takayabu 2018) as well as in the Tropics (Derbyshire et al. 2004; Kikuchi and Takayabu 2004; Takemi et al. 2004) and were also found in the environment for the July 2018 heavy rainfalls (TU19). Therefore, middle-level humidity would contribute to extremely large PW in the present case.

As shown in Fig. 3, MAUL is considered to be a key factor for increasing the potential for the present heavy rainfalls. The MSM data were used to determine the horizontal extent and depth of MAUL. At every grid point we searched a convectively unstable layer from the lowest level, which met the relationship as follows:

$$\frac{\partial \theta_e}{\partial z} < 0 \text{ and } \mathrm{RH} > 99\%,$$

where θ_e is equivalent potential temperature and RH is relative humidity. Note that the stricter condition for moisture than used in Bryan and Fritsch (2000) is employed here because of potential errors in moisture representations in the MSM data. The depth of MAUL was determined as the continuous layer that met the above relationship, and was computed at all the grid points.

Figure 6 demonstrates the distribution of the MAUL thickness at the same times as shown in Fig. 5. It is clearly seen that

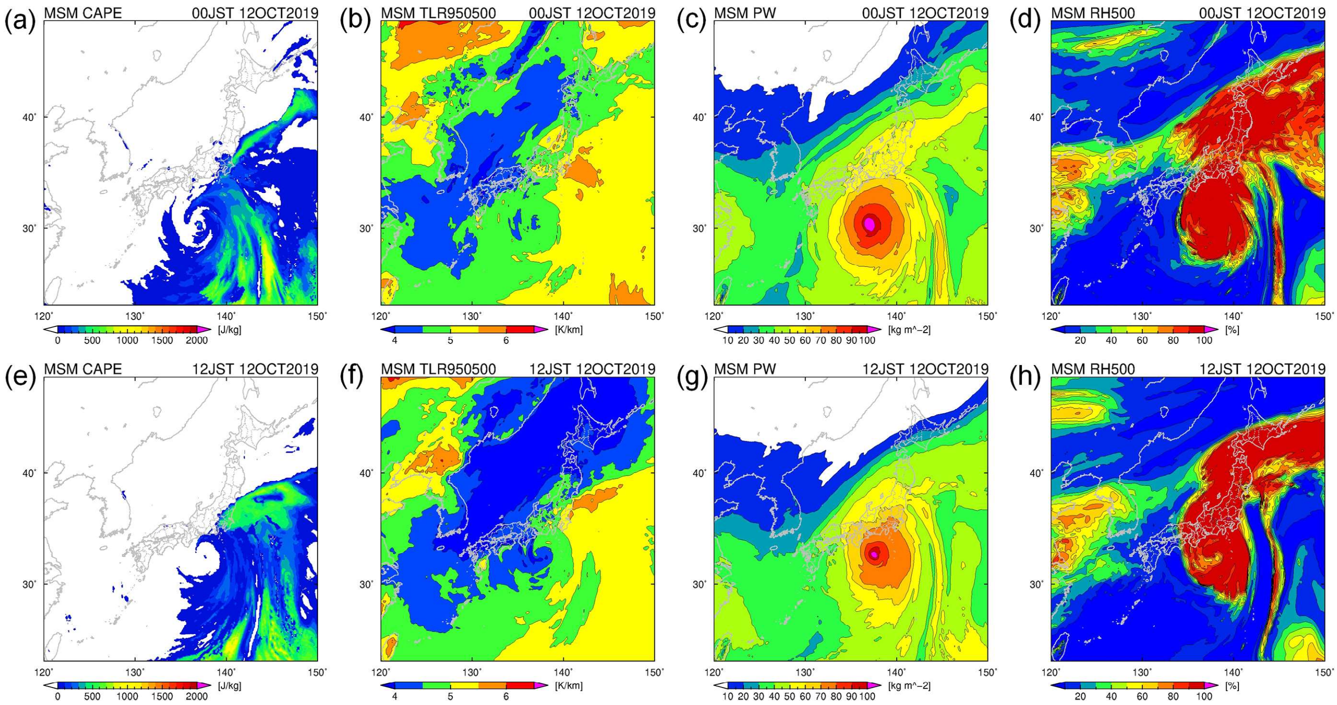

Fig. 4. The horizontal distributions of environmental parameters at 0000 JST 12 October (upper panels) and 1200 JST 12 October (lower panels). The values indicated are (a) (e) CAPE (J kg^{-1}), (b) (f) temperature lapse rate (K km^{-1}), (c) (g) precipitable water vapor content (kg m^{-2}), and (d) (h) relative humidity (%) at the 500-hPa level.

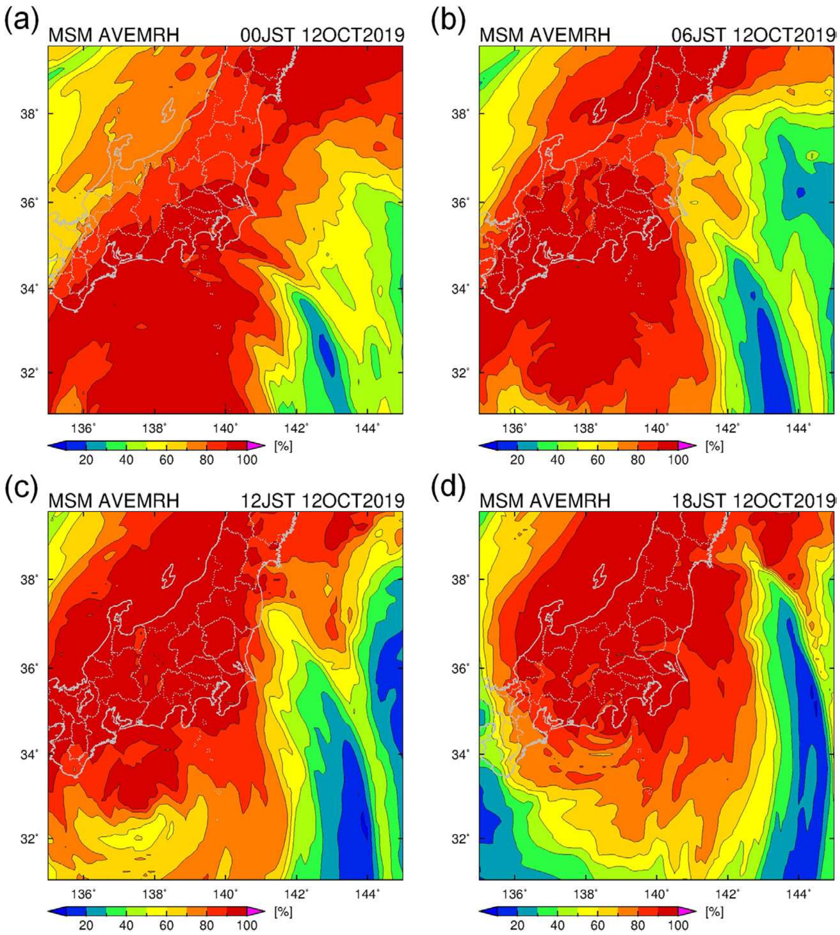

Fig. 5. The horizontal distribution of mean relative humidity (in %) vertically averaged in the 700–300 hPa layer at (a) 0000 JST, (b) 0600 JST, (c) 1200 JST, and (d) 1800 JST on 12 October 2019.

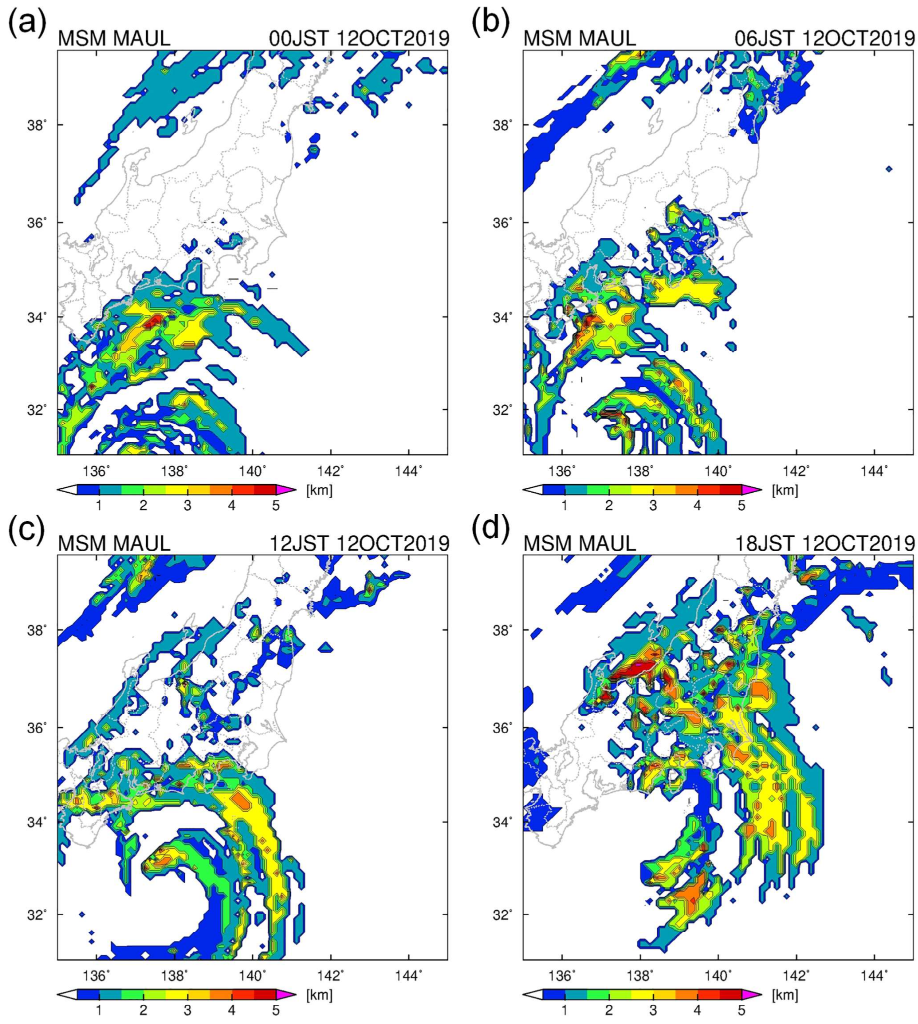

Fig. 6. The horizontal distribution of the thickness (in km) of moist absolutely unstable layer at (a) 0000 JST, (b) 0600 JST, (c) 1200 JST, and (d) 1800 JST on 12 October 2019.

MAULs appear within the humid regions shown in Fig. 5. The thickness of MAULs is mostly greater than 1 km and, with the typhoon translation, becomes deeper than 2 km. With the approach of such deep MAULs, the resulting total rainfalls in the following 6 hours are seen to increase and extend in wide areas (Figs. 2e, 2f, 2g, and 2h).

Bryan and Fritsch (2000) found that the mean depth of MAULs over the United States is 140.4 hPa. Although the climate of US and Japan is different, thickness of 2 km or deeper in Fig. 6 may be regarded as very deep. Despite moderate CAPE (Figs. 4a and 4e), the stability conditions on 12 October are absolutely unstable against moist-adiabat. These unstable conditions provide a high potential for convection. However, without any triggering, convection would not actually develop. One of the major triggering mechanisms is considered as topography-induced ascent. In order to obtain the insight of this topographic effect, we examine the bottom height of MAULs. If the bottom heights of MAULs are comparable to the mountain heights, the lifting by topography is expected to easily trigger convection.

The bottom heights of MAULs are displayed in Fig. 7. Focusing on the land regions, it is seen that the bottom heights are mostly lower than 4.5 km and in some areas below 2 km. On the other hand, the elevations of the mountains such as Tanzawa, Kanto, and Echigo Mountains are 1500−2500 m. Therefore, the MAUL bottoms are comparable to or a little higher than the mountain tops, which would be sufficient to trigger and activate convection in those mountainous regions.

4. Discussion

From observational and MSM data, the existence of MAULs has been demonstrated. Because of the absolute instability, the layer is highly unstable for convection development. Deep MAULs with their thickness greater than 2 km were found to widely extend over land regions while the typhoon moved northward. In addition, the PW amount was quite large, even compared with that seen in the July 2018 heavy rainfalls (TU19). Such a large PW amount directly contributes to the increase in rainfall. Thus, both convective instability under very humid conditions and a sufficient amount of moisture provide a high potential for the development of heavy rainfalls.

Under such a highly unstable potential, triggering from topography is considered to play a critical role in activating convection. Because the topographic effect may not be directly shown by the MSM data, the effect was diagnosed in terms of the bottom height of MAULs. The height of the MAUL bottom was found to be comparable to or a little higher than the mountain tops, which is considered to play a triggering role.

Bryan and Fritsch (2000) showed that MAULs exist in conjunction with MCSs. In the present case, the circulations associated with Typhoon Hagibis is considered to maintain the moist absolutely unstable state. A particular feature of the present case is that under almost saturated conditions throughout the troposphere the PW amount is extremely large. Such a large amount of

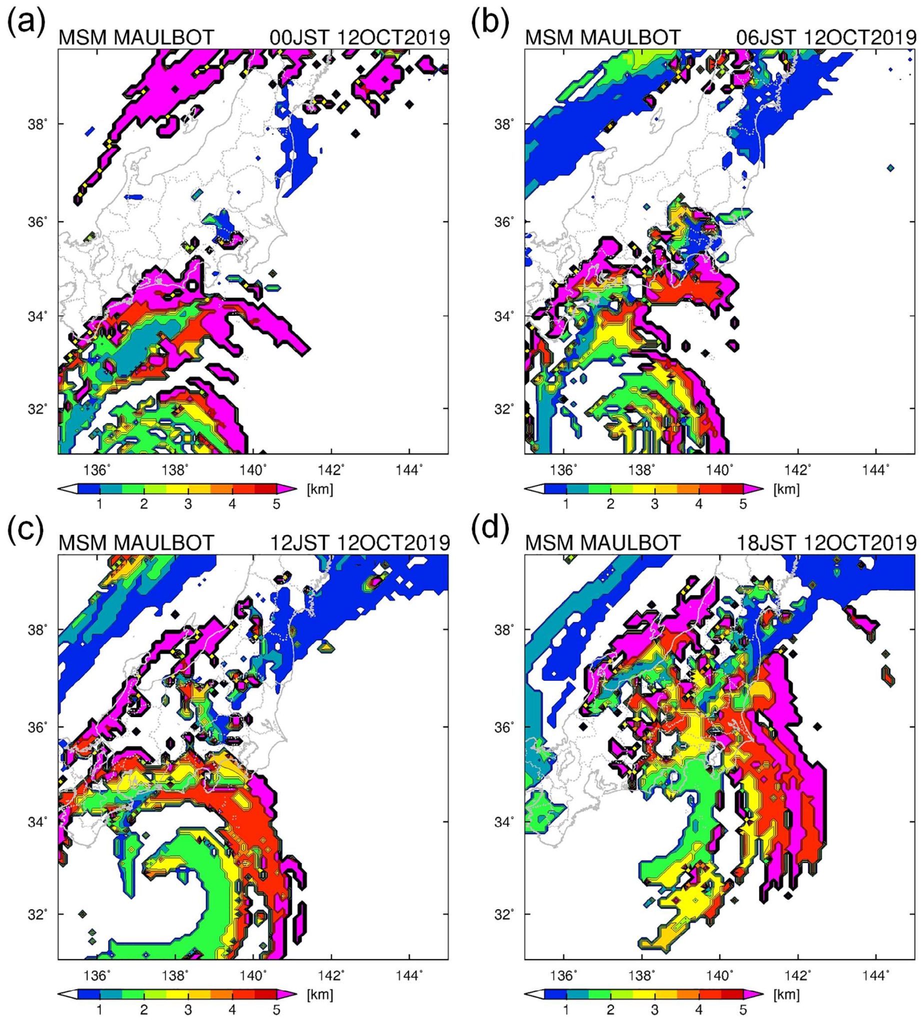

Fig. 7. The same as Fig. 6, except for the bottom level (km) of moist absolutely unstable layers.

moisture as well as deeper MAULs will compensate for moderate CAPE conditions.

In general, the CAPE values on the Honshu Island of Japan during the warm season are on the order of 100 J kg^{-1} (Chuda and Niino 2005; UT16), which are much lower than those found in the cases of MCSs over the United States (e.g., Bluestein and Jain 1985). The difference is considered to be due to the difference in temperature lapse rate. Lucas et al. (1994) compared the buoyancy of adiabatically lifted air parcels between tropical-oceanic and midlatitude-continental environments and found that the buoyancy in the tropical environment is smaller, which is due to the difference in the lapse rate between the two environments. Thus, the temperature lapse rate somehow controls the CAPE value.

According to the statistical analyses, UT16 indicated that the temperature lapse rate below the 500-hPa level is around 6 K km^{-1} for the cases of quasi-stationary convective systems during the warm season, and Kato et al. (2007) demonstrated that the lapse rate below middle-levels during the Baiu season is below about 6 K km^{-1}. For the July 2018 heavy rainfalls, the lapse rate below the 500-hPa level was around 5.5 K km^{-1}. Thus, TLR in the present case is regarded as quite normal. Therefore, the stability condition in the present case, as in other cases in Japan, is closer to the tropical-oceanic environment in which temperature lapse rate is closer to the moist-adiabat than that in the midlatitude-continental case. Under such moist environments, moist absolutely unstable states are considered to play an important role in enhancing rainfalls.

5. Conclusions

This study investigated the factors responsible for the development of heavy rainfalls during the passage of Typhoon Hagibis (2019) from a thermodynamic point of view. We specifically focused on the temperature and moisture conditions through examining some of widely used environmental indices. By using the mesoscale analysis data as well as the observed data, we found that moist absolutely unstable states under very humid conditions throughout the troposphere and a sufficient amount of precipitable water characterize the environmental conditions for the development of heavy rainfalls.

The concept of MAUL put forth by Bryan and Fritsch (2000) was found to be quite useful in understanding the environmental factors for the present case. The present sounding data demonstrated the existence of MAULs. After validating the usefulness of the mesoscale analysis data against the sounding data, we showed the horizontal distributions of the atmospheric instability, the moisture content, and the middle-layer relative humidity. It was indicated that deep MAULs, high relative humidity throughout the troposphere, and an abundant moisture content jointly set favorable conditions for the heavy rainfalls. With such high potential, lowered heights of the MAUL bottom comparable to the mountain heights are favorable for topographic lifting, which in turn trigger and activate strong convection and hence heavy rainfall.

This study preliminary presented the environmental characteristics for the heavy rainfalls induced by Typhoon Hagibis.

Although the MAUL concept was found to explain the stability conditions, the statistical features of MAULs in rainfall cases need to be further investigated. As indicated in this study, the mesoscale analysis data well reproduce the actual atmospheric conditions and hence should be useful in such statistical studies.

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Supplements

Supplement 1: The comparison of the MSM data against sounding observations.

Supplement 2: The geographical map of the central and eastern parts of Japan.

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