The Role of Free-Tropospheric Moisture Convergence for Summertime Heavy Rainfall in Western Japan

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Abstract The role of vertically integrated water vapor flux convergence (IVFC) in heavy rainfall events in western Japan is investigated by dividing the atmosphere into a boundary layer and free troposphere using the Japan Meteorological Agency's mesoscale gridded analysis product and reanalysis product. Rainfall events are defined by peaks of area-averaged precipitation. The results show an increase in the free-tropospheric IVFC more than 15 h before rainfall events, contributing to atmospheric moistening. This preceding moistening is favorable for mesoscale convective systems (MCSs) with slantwise ascending deep inflow layers (layer lifting) that produce large precipitation amounts. Appearance frequency of the moist absolutely unstable layer (MAUL) increases around the precipitation peak times, which is especially notable for larger peaks. These results indicate that the free-tropospheric IVFC contributes to heavy rainfall in western Japan by providing environments favorable for producing and maintaining MAUL, enhancing the organization of MCSs.

Plain Language Summary The role of moisture convergence for heavy rainfall events in western Japan is investigated by dividing the atmosphere into its lowest part (boundary layer) and layers above it (free troposphere). Our results indicate that free-tropospheric moisture increases earlier than 15 h before peak rainfall, contributing to atmospheric moistening. This moistening in the free troposphere is favorable for developing MCSs with slantwise ascending deep inflow layers, which produce large amounts of precipitation. These results indicate the significance of free-tropospheric moisture convergence to rainfall events over western Japan.

1. Introduction

Severe weather events are often associated with mesoscale convective systems (MCSs) (Breugem et al., 2020; Doswell et al., 1996; Maddox, 1980). The characteristics of MCSs causing rainfall events in East Asia are different from those in the United States (Hong, 2004; Sohn et al., 2013). In the United States, MCSs often develop in dry continental environments with high convective available potential energy (CAPE). Intense vertical velocities and hailstorms characterize such MCSs. In East Asia, MCSs develop in moister environments associated with the East Asian summer monsoon (Yokoyama et al., 2014).

MCSs in moist environments are characterized by a slantwise ascending deep inflow (layer lifting) and a moist absolutely unstable layer (MAUL) (Bryan & Fritsch, 2000; Houze, 2004, 2018). The MAUL forms when destabilization by saturation is faster than the release of instability by buoyancy (Bryan & Fritsch, 2000). Environments favorable for the organization of MCSs with layer lifting are characterized by high moisture contents above the boundary layer, moderate CAPE, and strong low-level shear with low-level jet (e.g., Alfaro, 2017; Choi et al., 2011; James et al., 2005; Schumacher, 2009; Schumacher & Johnson, 2008, 2009). Particularly, free-tropospheric moisture is an essential factor for layer lifting. Mechem et al. (2002) showed that an increase in moisture in the mid-troposphere causes layer lifting overturning. Even for MCSs developed under relatively dry environments, inflow air is moistened by precipitation falling into the inflow layer when layer lifting is observed (Parker, 2007; Parker & Johnson, 2004). Although moist environments are detrimental to generating cold pools that can enhance layer lifting (Bryan & Parker, 2010; James et al., 2005), a gravity wave response to a quasi-steady diabatic heating associated with convection produces a mesoscale circulation, helping to generate the slantwise ascent in MCSs in moist environments (Fovell, 2002; Pandya & Durran, 1996).
Previous studies indicate that MCSs with layer lifting sometimes produce more precipitation than precipitation systems composed of tall convections originating from the boundary layer with unstable environments. Hamada et al. (2015) statistically showed a weak linkage between extreme convection and extreme precipitation events using satellite radar observation data. Extreme convection and extreme precipitation are defined by the uppermost 0.1% values of maximum 40-dBZ echo-top heights and surface precipitation, respectively, at each 2.5° × 2.5° grid cell. They also showed that the environments in the extreme precipitation events are moister and more stable than those in the extreme convection events. Additionally, Hamada and Takayabu (2018) showed, from similar analyses around Japan in summer season, that extreme precipitation events are characterized by larger system sizes, higher stratiform precipitation ratios, and smaller flash rates than those for extreme convection events. These results indicate that extreme precipitation events occur in environments favorable for the organization of MCSs with layer lifting. This conclusion is consistent with previous studies, indicating that well-organized systems in moist environments with layer lifting have wide stratiform precipitation areas (Kingsmill & Houze, 1999; Mechem et al., 2002), producing large amounts of precipitation (Ahmed & Schumacher, 2015; Zhang & Wang, 2021). Zheng et al. (2013) statistically showed that MCSs in moist environments during the monsoon season over China also produce more precipitation than those in dry environments in the premonsoon season.

Some studies of heavy rainfall events in East Asia reported environments favorable for layer lifting organization (e.g., Hirota et al., 2016; Jeong et al., 2012, 2014; Saito & Matsunobu, 2020; Tsuji & Takayabu, 2019; Yokoyama et al., 2020). Moreover, some case studies specify the role of MAUL (Choi et al., 2011; Takemi & Unuma, 2020). However, many studies on rainfall events in Japan emphasized the importance of parameters related to the boundary layer only and underestimated the role of free-tropospheric moisture convergence (e.g., Araki et al., 2021; Kato, 2018, 2020; Tsuguti & Kato, 2014).

In this study, we compare the time evolutions of moisture flux convergence in the boundary layer and in the free troposphere associated with heavy rainfall events around Kyushu, Japan, where disastrous rainfall events frequently occur (Araki et al., 2021; Hirockawa et al., 2020; Tsuji et al., 2020), to clarify the role of moisture above the boundary layer. We show that free-tropospheric moisture flux convergence provides environments favorable for the organization of MCSs with layer lifting before rainfall events.

2. Data and Methodologies

2.1. Data and Analysis Period

The initial forecast values of the Japan Meteorological Agency (JMA) operational Mesoscale Model (MSM) (JMA, 2019) are used in the analysis. We use the 3-hourly grid point values of horizontal winds, temperature, geopotential height, and relative humidity. These data have a horizontal resolution of 0.125° longitude × 0.1° latitude and 16 vertical layers, covering a region around Japan (120–150°E, 22.4–47.6°N). We also use a 6-hourly Japanese 55-year global atmospheric reanalysis (JRA55) product (Kobayashi et al., 2015) with 1.25° × 1.25° resolution and 37 vertical layers in order to investigate the synoptic environment including outside areas covered by the MSM product. In addition, the JMA best-track data is used to identify the tropical cyclone locations.

MSM produced hourly precipitation is also used. This product has a horizontal resolution of 0.0625° longitude × 0.05° latitude. We use this precipitation product after converting it into 3-hourly data. In addition, the Automated Meteorological Data Acquisition System (AMeDAS) rain gauge data are used to validate the MSM precipitation. The analysis period is from June to August of 2006–2020.

2.2. Definitions and Calculation Methods

Rainfall events are defined by peaks of area-averaged precipitation over the Kyushu region (30–35°N, 128.75–132.5°E; Figure S1) that exceed certain thresholds. We set three categories for the precipitation peaks: 20–40, 40–60, or over 60 mm day⁻¹.

Vertically integrated water vapor flux convergences (IVFCs) in the Kyushu region are calculated using the MSM and JRA55 products. The water vapor flux convergence at each layer is calculated using the Green's theorem. The total IVFC is calculated by integrating the flux convergence at each layer from 1,000 to
300 hPa. Free-tropospheric IVFC and boundary-layer IVFC are defined with vertical integrations in the 900–300-hPa and 1,000–900-hPa layers, respectively. Here, we divide the atmosphere into the boundary layer and free troposphere at 900 hPa because some studies on heavy rainfall events in Japan emphasize the largest contribution of moisture convergence below 900 hPa (Kato, 2018). We examined the sensitivity to the choice of the boundary using the values 850 and 800 hPa, and obtained the same conclusion.

The total IVFC is a part of the water vapor budget equation

\[
\frac{\partial \text{PW}}{\partial t} = \frac{1}{g} \left[ \frac{\partial}{\partial z} \left( -\nabla \cdot q \vec{v} \right) \right] dp - P + E,
\]

where \( \text{PW} \), \( g \), \( q \), \( \vec{v} \), \( P \), \( p \), \( p_1 \), \( p_2 \), and \( t \) denote precipitable water, gravity acceleration, mixing ratio, horizontal wind, precipitation, evaporation, pressure, 1000 hPa, 300 hPa, and time, respectively. Note that evaporation around the Kyushu region in summer is considered relatively small because of the moist environment (e.g., Zhao et al., 2021). Therefore, the IVFC corresponds well to precipitation around the precipitation peaks (c.f., Figure 1). We analyzed the rainfall events defined by IVFC peaks and reached the same conclusion.

The precipitable water tendency within the Kyushu region is defined as the average over all grids within the region. Precipitable water is calculated through the vertical integration of the mixing ratio from 1,000 to 300 hPa.

The MAUL condition is defined following Takemi and Unuma (2020) as

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

where \( \theta_e \), \( z \), and RH are the equivalent potential temperature, height, and relative humidity, respectively. This definition is stricter than that used in Bryan and Fritsch (2000), considering potential errors in moisture representations in the MSM (Takemi & Unuma, 2020).
2.3. Compositing Method

We make composites centered at the precipitation peaks. If another precipitation peak is found within ±24 h from a peak, the smaller one is discarded from the composite. In addition, if tropical cyclones are located within ±5° from the Kyushu region (blue box in Figure S1) at a peak time, the peak is discarded to exclude the effects of tropical cyclones. The numbers of peaks used in the composites of the 20–40-, 40–60-, and over 60-mm day$^{-1}$ categories are 105, 77, and 62, respectively. Composite values are normalized using these sample numbers. Similar composites with IVFC peaks are made to confirm the robustness of our conclusions (Supporting Information S1), and their peak numbers are listed in Table S1.

3. A Sample Case

Figure 1 shows time evolutions of IVFC, precipitation, and precipitable water tendency of a sample rainfall case in which the precipitation peak occurred at 12 JST July 8, 2016 (JST = UTC + 9). Before the precipitation peak, the free-tropospheric IVFC started to increase at 03 JST 7 July, a day earlier than that of the boundary-layer IVFC, which started to increase at 03 JST 8 July. Positive precipitable water tendency is analyzed when the free-tropospheric IVFC increased. The precipitation began to increase sharply at 21 JST 7 July, after an increase in the free-tropospheric IVFC increased. These results suggest that the free-tropospheric IVFC provides a moist environment before the precipitation increase. A precipitation distribution and a satellite image at the peak time (Figures 2a and 2b) show an MCS with a few line-shaped intense
Figure 2c shows a vertical cross-section of the inflow and equivalent potential temperature along the white line in Figure 2a. Notably, an intense (over 20 m s$^{-1}$) and deep (~5,000 m) inflow layer are slantly lifted northward. The areas satisfying the MAUL condition, depicted by the black open circles, are diagnosed where the inflow layer is lifted (30.8–31.2°N). These characteristics are also analyzed at the next time step (Figure S2). Such distributions of inflow and MAUL are very similar to those of the cross-section through the ideal slab convective overturning (Figure 5 in Bryan & Fritsch, 2000).

4. Composite Results and Discussions

The example case described above shows that the free-tropospheric IVFC provides a moist environment before heavy rainfalls and that a MCS with layer lifting produces intense precipitation. Next, we make composites by aligning the precipitation peaks (Figure 3) to confirm the generality of such indications. For every precipitation areas developed around Kyushu Island. Such line-shaped precipitation areas along the inflow often appear over East Asia (e.g., Johnson et al., 2005; Kato, 2020).

Figure 3. Time evolutions of the total integrated water vapor flux convergence (IVFC) (black), boundary-layer IVFC (red), free-tropospheric IVFC (blue), precipitation (purple), and precipitable water tendency (green) composites for aligning the precipitation peaks of the (a) 20–40 mm day$^{-1}$, (b) 40–60 mm day$^{-1}$, and (c) over 60 mm day$^{-1}$ composites calculated using MSM products. Error bars for the boundary-layer and free-tropospheric IVFC indicate ranges in 95% confidence level calculated using Student’s t-test. The abscissa indicates the time from the precipitation peak (hr).
category, the free-tropospheric IVFC starts to increase before the boundary-layer IVFC increases. Moreover, the free-tropospheric IVFC starts to increase earlier for the 40–60-mm day$^{-1}$ and over 60-mm day$^{-1}$ composites (−39 h) than for the 20–40-mm day$^{-1}$ composite (−15 h). In contrast, the boundary-layer IVFC experiences little change before −9 h in all composites. The changes in the precipitable water tendency follow those in the free-tropospheric IVFC, preceding well to the boundary layer IVFC. This is appearing more clearly in the heavier precipitation composite (Figure 3c). These results suggest that the free-tropospheric IVFC contributes to the build-up of moist environments before rainfall peaks, as shown in the example case.

The same conclusions are obtained when composites are made by aligning the total IVFC peaks calculated using the MSM (Figure S3) and JRA55 (Figure S4) products. Moreover, the evolution of composited precipitation is qualitatively similar to that of the AMeDAS gauge data (Figure S5).

The preceding increase in the free-tropospheric IVFC is also confirmed in horizontal maps (Figure 4). At 12 h before the peak (Figures 4a and 4b), the boundary-layer IVFC is distributed around the East China Sea, whereas the free-tropospheric IVFC covers the Kyushu region. At the peak time (Figures 4c and 4d), intense boundary-layer IVFC is found west of Kyushu Island, whereas intense free-tropospheric IVFC is found east of Kyushu Island. After the peak time (Figures 4e and 4f), the boundary-layer IVFC covers the Kyushu region and western Japan, whereas the free-tropospheric IVFC is analyzed over the Kyushu region; the convergence area is analyzed over eastern Japan.

Southwesterly water vapor flux comes from southern China and the western Pacific. Such moisture flux patterns are consistent with the composite of the extreme precipitation events in Hamada and Takayabu (2018).
Moreover, some studies on rainfall events around Japan showed similar moisture flux patterns (e.g., Akiyama, 1975; Ninomiya, 1978, 2000; Takemura et al., 2019; Zhao et al., 2021). The eastward propagation of the IVFC center is associated with a cyclonic anomaly located around the Korean Peninsula (Figure 4). Such synoptic disturbance contributes to preparing moist environments favorable for heavy rainfalls (Nie & Fan, 2019; Shibuya et al., 2021).

The numbers of MAUL grids within the Kyushu region are also composited to confirm the existence of MAUL associated with layer lifting in MCSs in tandem with heavy precipitation (Figure 5). The vertically integrated numbers of MAUL grids steeply increase around the peaks for all composites (Figures 5a–5c). The number at peak time increases with peak precipitation. These figures show the apparent increases of the MAUL condition associated with heavy rainfalls, indicating that convection is occurring in these grids. Moreover, the increase in the number of MAUL grids occurs at 500–800 hPa (Figures 5d–5f), consistent with the results of Bryan and Fritsch (2000). These results indicate that these MAUL conditions are associated with MCSs with layer lifting at around the precipitation peak time. We can find other cases of the slantwise deep inflow layer with MAUL, similar to those shown in Figure 2, in extreme rainfall events in July 2020 and July 2018 (not shown). These results suggest the ubiquity of such events where free-tropospheric IVFC contributes to develop the MAUL condition associated with layer liftings in organized MCSs and causes heavy rainfall events over the Kyushu region. On the other hand, we can also find other cases in which atmospheric instability causes heavy rainfall. An example is a heavy rainfall in July 2017 in the Northern Kyushu region (Tsuj et al., 2020). It is reported that MAUL hardly contributed to the heavy rainfall in this

Figure 5. Time evolution of the average number of moist absolutely unstable layer grids for the (a), (d) 20–40-mm day$^{-1}$, (b), (e) 40–60-mm day$^{-1}$, and (c), (f) over 60-mm day$^{-1}$ precipitation peak categories calculated using the MSM products. Panels (a–c) show the vertically integrated number of grids, and panels (d–f) show the vertical distribution of the averaged numbers.
The contrasts in precipitation characteristics and environmental conditions between the 2018 and 2017 cases are discussed in details in Tsuji et al., (2020).

Although uplifting mechanisms producing the slantwise ascent and MAUL for each rainfall case are not investigated due to insufficient spatiotemporal resolution of the data, some mechanisms are inferred from previous studies. One possible uplifting mechanism is a mesoscale circulation as a gravity-wave response to a quasi-steady diabatic heating associated with convection in the MCSs, suggested by some previous studies (e.g., Fovell, 2002; Pandya & Durran, 1996). Liu and Moncrieff (2017) performed numerical simulations to investigate organized convection observed in the Asian summer monsoon and pointed out a vital role of convectively generated gravity waves. Other lifting mechanisms such as orographic lifting (e.g., Takemi & Unuma, 2020) and lifting associated with cold pool outflow (e.g., Bryan & Fritsch, 2000; James et al., 2005) also can provide the slantwise ascent in some cases. Further investigation about the uplifting mechanism is future work.

5. Conclusions

Composites with aligned precipitation peaks show that the free-tropospheric IVFC provides a moist environment before rainfall events over the Kyushu region. Moist environments are favorable for MCSs organized with layer lifting, which produces the MAUL condition and heavy precipitation. This preceding moistening is more pronounced in composites with more intense precipitation peaks and hence heavier rainfall events. The MAUL conditions primarily occur in the mid-troposphere around 600 hPa, especially for intense precipitation composites around the peak time, indicating that layer liftings associated with MCSs sustain favorable conditions for heavy rains. These results indicate the significant role of moistening above the boundary layer for rainfall events over the Kyushu region.

Because environments favorable for layer lifting are observed in rainfall events in Korea (Choi et al., 2011; Jeong et al., 2014) and nocturnal MCS cases in the United States (Schumacher and Johnson, 2008, 2009), similar results are expected in other regions worldwide. In future research we will investigate where in the world MCSs with layer liftings and MAUL cause rainfall events.

Data Availability Statement

The MSM products were obtained from the database of Research Institute for Sustainable Humanosphere, Kyoto University. The JRA55 products, AMeDAS data, and JMA besttrack data were provided by JMA. Himawari 8 gridded data are distributed by Center for Environmental Remote Sensing (CEReS), Chiba University, Japan. These are available at following URL: MSM: http://database.rish.kyoto-u.ac.jp/arch/jmadata/data/gpv/original/ JRA55: https://jra.kishou.go.jp/JRA-55/index_en.html AMeDAS: https://www.jma.go.jp/bosai/amedas/#area_type=japan&area_code=010000&lang=en JMA besttrack: https://www.jma.go.jp/jma/jma-eng/jma-center/rsme-hp-bug-besttrack.html Himawari 8: http://www.cr.chiba-u.jp/databases/ GEO/H8_9/FD/index.html.

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