

Analysis and Numerical Modeling of Linear-Shaped Mesoscale Convective Systems

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ABSTRACT

A linear-shaped mesoscale convective system (MCS) is one of the major forms of organized deep convection. A moving linear-shaped MCS is known as a squall line. This chapter focuses on how the development and intensity of linear-shaped MCSs are affected by environmental stability and humidity conditions. Numerical experiments with idealized settings indicated that the intensity of convective updrafts within simulated linear-shaped MCSs becomes weaker under tropical/oceanic conditions than under midlatitude/continental conditions. The dependence of the convective intensity on the free tropospheric humidity appears differently in environments with different temperature lapse rate. The analysis on the climatological characteristics of quasi-stationary MCSs in Japan, as a case of MCSs that develop in humid climate regions, indicated that middle-level relative humidity controls the development of such MCSs and also that linear-shaped MCSs preferably occur with a certain amount of vertical shear. High-resolution modeling of a linear-shaped MCS demonstrated that the horizontal resolution of about 100 m is able to capture the successive development of convective cells on the upstream side of a linear-shaped MCS and the stationarity of the MCS as a whole through representing more precisely a complex and complicated nature of topography and explicitly resolving convective motion.

KEY WORDS: mesoscale convective system, squall line, linear-shaped mesoscale convective system, convective organization, environmental control, mesoscale meteorological modeling

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1. INTRODUCTION

Deep cumulus clouds organize as mesoscale systems when appropriate environmental conditions develop. Mesoscale convective systems (MCSs) can occur in various climate regions of the world and sometimes cause severe weather such as strong winds, heavy rainfalls, and hailfalls. Understanding and predicting the processes related to MCSs and resulting severe weather are challenging issues in mesoscale meteorology and weather forecasting. Furthermore, environmental changes under future global warming are anticipated to worsen the threat of severe weather resulting from MCSs. Assessing the impacts of climate change is also critically important to design adaptation strategy and measure against severe weather in a future warmed climate.

MCSs develop in various forms. The morphology of MCSs can be classified as a linear and a circular type; a linear-type MCS is called as a squall line, while a circular-type MCS as a cloud cluster or mesoscale convective complex (Maddox, 1980). Among these MCSs, squall lines have been extensively investigated in the literature. With the development of precipitation radar networks, the convective-scale processes and organization modes of squall lines have been able to be examined in detail. A pioneering work of Bluestein and Jain (1985) demonstrated, through examining the radar images of squall lines in the central plains of the United States, that the distinguishing mode of squall line organization was classified into 4 types: broken line; back building; broken areal; and embedded areal. The environmental properties that distinguish these squall-line modes were found to be vertical shear in the lower troposphere and convective instability.

From theoretical and numerical studies, vertical shear in the troposphere has been shown to determine the organization mode of MCSs (Weisman and Klemp, 1982; Rotunno et al., 1988; Fovell and Ogura, 1989; Weisman, 1992; Robe and Emanuel, 2001; Weisman and Rotunno, 2004). Observationally, LeMone et al. (1998) indicated that the intensity of vertical shears at different height levels (i.e., low-level versus middle-level) characterizes the direction and shape of squall lines in tropical oceanic regions. Parker and Johnson (2000) demonstrated that the magnitude and direction of the tropospheric vertical shear affects the shape and evolution of midlatitude squall lines with stratiform precipitation. The organization mode of squall lines was further investigated for those occur in east China and found to form generally in a broken-line mode with a trailing-stratiform pattern (Meng et al., 2013). Unuma and Takemi (2016a) examined the morphology of meso- β -scale, quasi-stationary convective clusters (Unuma and Takemi, 2016b) and found that the vertical shear in the lower troposphere is a distinguishing factor which determines the shape of quasi-stationary convective clusters as a linear or a circular shape. In this way, the role of vertical shear has been recognized to significantly affect the organization mode and morphology of MCSs, especially squall lines.

Compared with the role of shear, the effects of convective instability have not well been explored. In the moist atmosphere, the amount of water vapor influences the stability conditions and hence should be considered in delineating the stability control of MCSs. A study that investigated the sensitivity to convective instability was conducted by Weisman and Klemp (1982) who numerically showed that the mode of convective storms can be categorized as a multi-cellular or supercellular type depending on the stability and shear conditions. In their study, a low-level moisture content was systematically changed in order to set various stability conditions under a prescribed vertical shear. It should be noted that in Weisman and Klemp (1982) the continental, midlatitude region was assumed in setting the vertical profiles of temperature, humidity, and winds; therefore, strong cold pools are generated and play a major role in developing and maintaining MCSs under moderate-to-strong shear conditions. For tropical MCSs, Barnes and Sieckman (1984) pointed

out that fast-moving squall lines which develop in drier middle-level environments are stronger than slow-moving counterparts, but, on the other hand, LeMone et al. (1998) suggested that a drier condition in the free troposphere below the 500-hPa level shorten the lifetimes of slow-moving lines. Thus, there are arguments on how tropical squall lines respond to the changes in the moisture. Actually, a study with the use of two-dimensional numerical experiments indicated that the squall-line properties vary significantly with changes in free-tropospheric humidity and shear profiles (Lucas et al., 2000). The impacts of environmental stability conditions on the structure and organization of MCSs should be systematically investigated.

With this recognition, a series of studies by Takemi (2006; 2007a; 2007b; 2010; 2014) conducted numerical experiments of linear-shaped MCSs, i.e., squall lines, under idealized environmental conditions with the vertical profiles of wind, temperature, and moisture being systematically varied and investigated how squall lines develop in response to these different conditions of shear and stability. In this chapter, reviewing those studies, we will firstly describe and summarize how the environmental stability and shear conditions affect and determine the development and organization of squall lines. Secondly, we will present the characteristics of MCSs that develop during the warm season over Japan, as an example of those occurring in humid climate regions. Quasi-stationary MCSs are specifically focused on. Then, we demonstrate the representation of a stationary, linear-shaped MCS in high-resolution numerical modeling from a case study on an extreme-rain-producing system over Japan. Finally, we will give concluding remarks and summarize this chapter.

2. IDEALIZED MODELING OF SQUALL LINES IN VARIOUS STABILITY CONDITIONS

2.1 Problem Setting

The strength of convective updraft depends on the tropospheric potential instability, according to the conservation law of mechanical energy in which potential energy can be converted to kinetic energy. The potential instability for the convective motion in the atmosphere can be diagnosed in terms of convective available potential energy (CAPE). Zipser and LeMone (1980) and Jorgensen and LeMone (1989) showed that the strength of convective updraft in thunderstorms is stronger in the midlatitude case than in the tropical case. In Jorgensen and LeMone (1989), the updraft strength was compared for cases in the tropics, sub-tropics, and midlatitude regions and was qualitatively estimated via the value of CAPE. From the conservation law of mechanical energy, CAPE for an air parcel at the surface will be converted to the kinetic energy whose velocity corresponds to the magnitude of updraft at the level of neutral buoyancy. Although in the real atmosphere the mixing and diabatic processes will dilute the instability for an air parcel at the surface, the maximum updraft speed ($w_{\max}$), which would be achieved for the surface air parcel if lifted to the level of neutral buoyancy, can be diagnosed in terms of CAPE as follows:

$$w_{\max} = \sqrt{2\text{CAPE}}. \quad (1)$$

Note that, from a quantitative perspective, Eq. (1) neglects the pressure gradient force and turbulent mixing and thus should be regarded as a general guide to compare the updraft strength under different CAPE conditions. By examining

the vertical change of excess temperature for an air parcel from the ambient environment, Lucas et al. (1994a) noted that the area of the positive excess temperature is “skinny” over the ocean but is “fat” over the continental region of the United States. Figure 1 indicates how the environmental temperature affects the value of CAPE through the changes in the magnitude of the excess temperature. The skinny profile indicated by the green line in Figure 1 suggests that the smaller buoyancy for a lifted air parcel over the ocean is easily diluted with the environment through mixing (i.e., entrainment) when compared with a larger buoyancy over the continent in which the fat profile indicated by the blue line in Figure 1 is seen. In other words, updraft air parcels in midlatitude, continental convective clouds will be less diluted with their environments and can be more accelerated by positive buoyancy than the air parcels in tropical, oceanic convection.

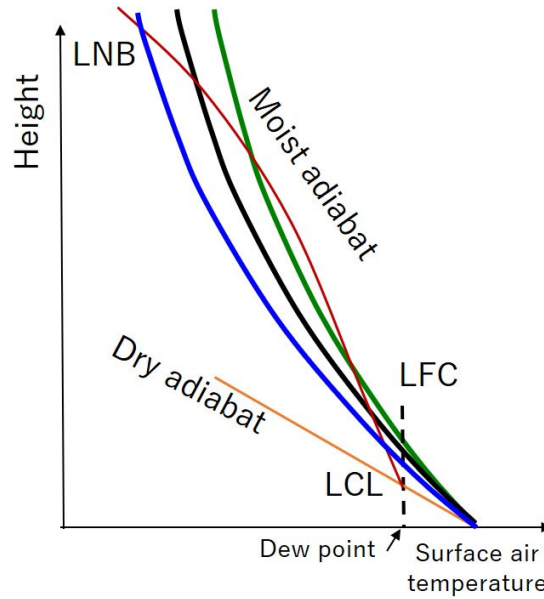


Figure 1. The conceptual diagram showing how the surface air parcel obtains the positive temperature excess from the environment through the adiabatic lifting. The surface air parcel is lifted firstly along the dry adiabatic line (the orange line) up to the lifting condensation level (LCL) and secondly along the moist adiabatic line (the red line) through the level of free convection (LFC) up to the level of neutral buoyancy (LNB). The environmental temperature profiles are denoted as the green, black, and blue lines.

Therefore, the magnitude of buoyancy (or positive temperature anomaly from the background state) has to be carefully examined in order to assess the updraft intensity. The excess temperature from the background depends on the temperature lapse rate of the background state. In drier climate regions such as midlatitude, continental regions, the temperature lapse rate becomes closer to dry-adiabat. On the other hand, in more humid climate regions such as tropical, oceanic regions, the lapse rate becomes closer to moist-adiabat. Such changes in the temperature lapse rate in various climate regions will lead to the difference in the intensity of updrafts in convective clouds. Xu and Randall (2001) showed that the largest difference between the tropical and midlatitude convection is seen for the strongest vertical velocity. McCaul et al. (2005) demonstrated that stronger updrafts in cooler environments are due to larger positive buoyancy from fusion processes that start at lower altitudes than in warmer environments. By keeping CAPE unchanged in various tropospheric temperatures in numerical experiments, James et al. (2006) indicated that convective clouds in warmer, moister environments, which are effective in reducing the evaporation rate, generate weaker cold pools, which determines the three-dimensional

structure of convective lines. By conducting numerical experiments, Houston and Niyogi (2007) further examined the influence of the temperature lapse rate above the level of free convection (LFC) on the development of cumulus convection and showed that stronger convection is produced under conditions with a larger temperature lapse rate.

In this way, the difference in the environmental temperature lapse rate is an important viewpoint to diagnose the strength of convective updraft and thus the organization and intensity of MCSs. Since the buoyancy depends not only on the properties of a low-level air parcel but also on the environmental temperature lapse rate, the vertical distribution of buoyancy is critically important for accelerating the air parcel upward (Lucas et al., 1994b; Takemi and Satomura, 2000; Takemi, 2010; Takemi, 2014). Therefore, the motivation of the idealized modeling of squall lines here is to investigate the sensitivity of the simulated squall lines to environmental stability conditions. In the followings, we will describe the design of numerical experiments and summarize the experimental results. We will then give implications for squall lines in the tropical, oceanic and the midlatitude, continental regions.

2.2 Experimental Design

In the studies of Takemi (2006; 2007a; 2007b; 2010; 2014), an idealized experimental approach was employed in order to focus on the dynamics of squall lines, as was done in Rotunno et al. (1988), Weisman et al. (1988), Fovell and Ogura (1989), Weisman (1992), Weisman and Rotunno (2004), etc. Here we specifically explain the experimental design employed in Takemi (2014).

The numerical model used here was the Weather Research and Forecasting (WRF) model, the Advanced Research WRF (ARW) version 3.1.1 (Skamarock et al., 2008). To conduct idealized experiments, the model was configured in a Cartesian computational domain of 300 km in the line-normal direction (east-west, referred to as x axis) by 60 km in the line-parallel direction (north-south, y axis) by 23 km (vertical, z axis), having minimum physics processes under horizontally homogeneous base states without the Coriolis force. The model physics here included cloud microphysics and turbulence mixing but ignored surface fluxes and atmospheric radiation. The cloud microphysics scheme employed here was the Goddard microphysics scheme (Tao et al., 1989; Tao and Simpson, 1993) which includes prognostic equations of the mixing ratios of water vapor, cloud water, rainwater, cloud ice, snow, and graupel, and the turbulence mixing was parameterized with the Deardorff scheme (1980) that solves a prognostic equation of turbulent kinetic energy to determine the eddy viscosity coefficient with the modification by Takemi and Rotunno (2003). The horizontal grid spacing was set to be 500 m, which was considered to be within a convection-resolving range. The vertical grid spacing was stretched with height, varied in the range of 45-900 m. The lateral boundary conditions were periodic at the north and south boundaries and open at the east and west boundaries. The lower boundary was free slip, as we ignored the surface fluxes for the present idealized numerical experiments. In the upper layer, a Rayleigh-type damping layer was imposed within the 5-km layer from the rigid-lid upper boundary to prevent unwanted reflections at the upper boundary.

The base-state conditions were set to represent a tropical, oceanic environment and a midlatitude, continental environment. The temperature profile of a tropical, oceanic environment was prescribed with sounding data obtained for squall line over the tropical western Pacific during the field observation of the Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA-COARE) in February 1993 (Trier et al., 1996). This environment will be hereinafter referred to as TROPICS. On the other hand, the midlatitude, continental profile was given with an analytical function representative of the environment for midlatitude convective storms (Weisman and Klemp,

1982). For the moisture profile, the data shown in Trier et al. (1996) were used to determine the TROPICS environment. For the moisture profile of the midlatitude environment, the analytical sounding of Weisman and Klemp (1982) was used and was divided into two types: a moist type (the original Weisman-Klemp humidity profile, referred to as MIDLATM) and a dry type (reduced humidity from the Weisman-Klemp profile, referred to as MIDLATD). The idea to define the dry type profile MIDLATD was to keep the vertical distribution of CAPE unchanged between the TROPICS and the MIDLATD environment. The vertical profiles of the base-state temperature and relative humidity in the cases of TROPICS, MIDLATD, MIDLATM are exhibited in Fig. 2.

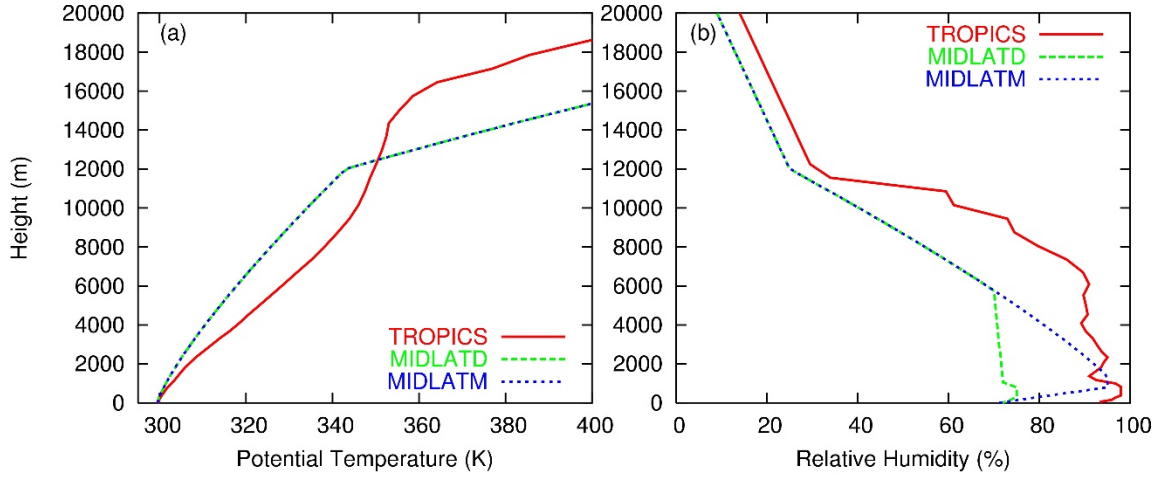


Figure 2. The base-state vertical profiles of (a) temperature and (b) relative humidity in the cases of TROPICS (red line), MIDLATD (green dashed line), and MIDLATM (blue dotted line). ©2014 Elsevier. Used with permission.

The vertical profile of base-state winds was prescribed as having a uni-directional shear profile in a certain layer and a constant wind profile above the shear layer. The prescribed shear layer was set either in the lower layer between 0 and 2.5 km (referred to as low-level shear) or in the middle layer between 2.5-5 km (referred to as middle-level shear) or in the deep layer between 0-5 km (referred to as deep shear). The magnitude of shear was chosen as the wind speed difference of 5 m s^{-1} and 15 m s^{-1} within the depth of 2.5 km (i.e., the low-level and middle-level shears) and the difference of 10 m s^{-1} within the depth of 5 km (i.e., the deep shear).

To initiate convection, we set either warm or cold linear-shaped potential temperature anomaly, aligned in the y direction placed at the central point of the x axis, having a peak value of +3 K for the warm thermal and -3 K for the cold pool with an elliptical shape in the $x - z$ cross section. A series of numerical experiments initialized by the warm line thermal and the cold pool was referred to as W-type and C-type, respectively. The conceptual diagram of the present numerical experiments is shown in Figure 3.

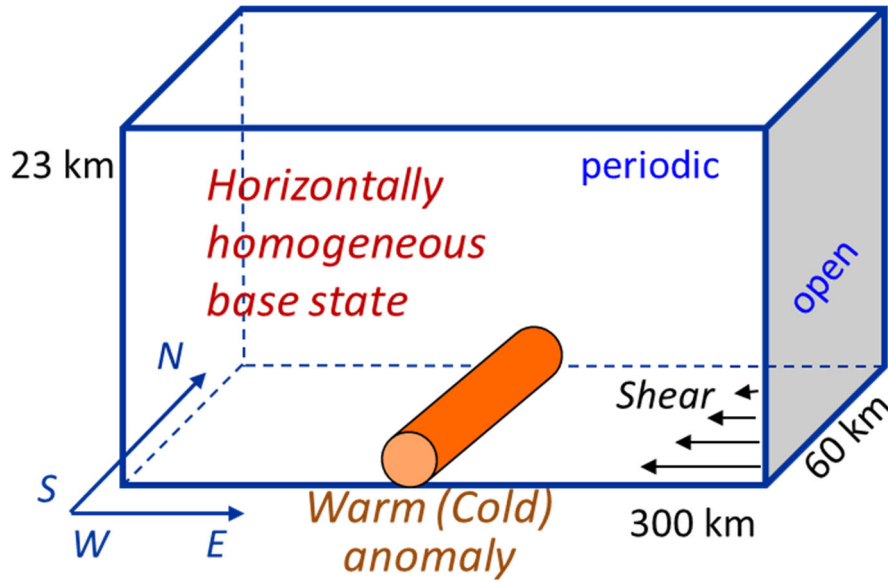


Figure 3. A conceptual diagram of the idealized experiments of squall lines.

2.3 Results

In this subsection, we demonstrate the results from the above-mentioned numerical experiments, which were fully described in Takemi (2014).

The features of the updrafts within the simulated squall lines under different stability conditions in the lower layer, strong shear case are compared in Figure 4. For the temporal averaged updraft speed, the both area-means and area-maxima are significantly stronger in the MIDLAT environment than in the TROPICS environment, except the case MIDLATD-W in which the convection did not develop with the warm thermal initialization in this drier case. The area size of stronger updraft ($w \geq 1 \text{ m s}^{-1}$) is much larger in MIDLAT than in TROPICS (except the MIDLATD-W case). The low-level strong shear seems to distinguish more clearly the differences between the MIDLAT and TROPICS cases than the low-level weak shear cases (see Figure 9 in Takemi, 2014). This is because the interaction between the low-level shear and a cold pool effectively strengthens the upward motion in cases which generate well-defined cold pools, according to the theory of Rotunno et al. (1988). The smaller fraction of strong updraft in the tropical environment seen in Figure 4b is consistent with an observational evidence (LeMone and Zipser 1980) and modeling studies (Tao et al., 1987; 2022).

In the elevated shear case shown in Figure 5, only the case MIDLATM-W case generates stronger and extensive updrafts within the simulated squall line. If a shear layer is elevated apart from the surface, the interaction between the low-level shear and the cold pool is less effective in order to sustain updrafts and hence convective systems, and therefore, the difference in the environmental stability will control more significantly the features of convective updrafts. Since the vertical profiles of CAPE between the TROPICS and MIDLATD environments are similar (see Figure 2), the updrafts features appear to be similar between these environments.

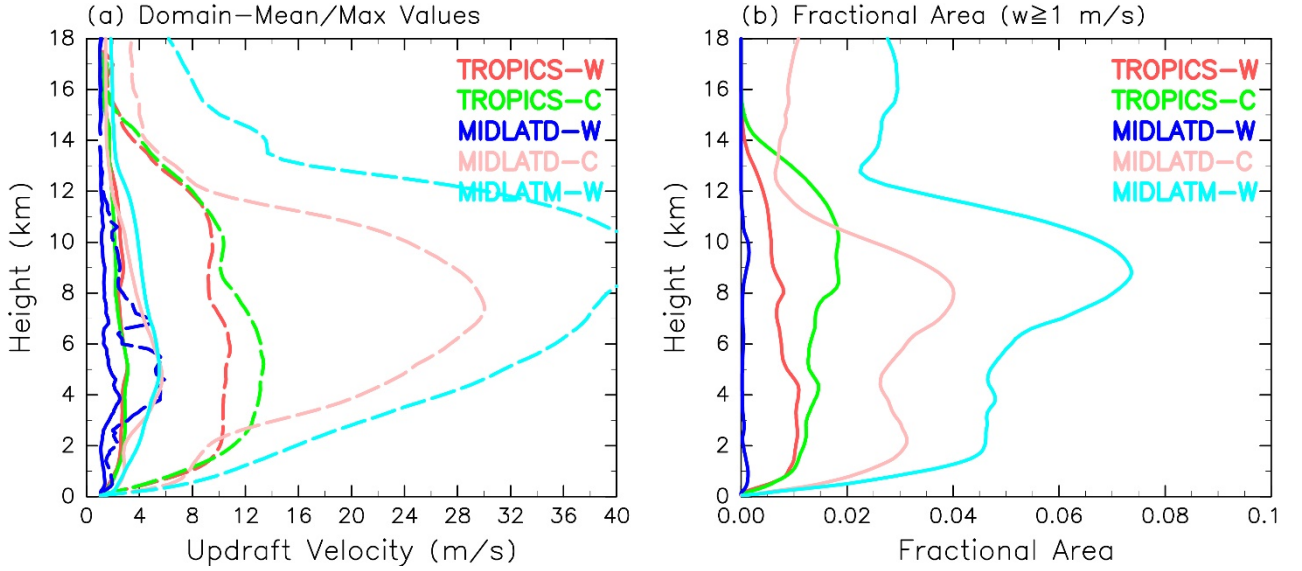


Figure 4. The temporal averaged vertical profiles of (a) the mean (solid lines) and the maximum (dashed lines) updraft speed over the updraft grids and (b) the fractional area of updraft grids over the computational area for the case of the low-level, strong shear (15 m s^{-1} in the 0-2.5 km layer).

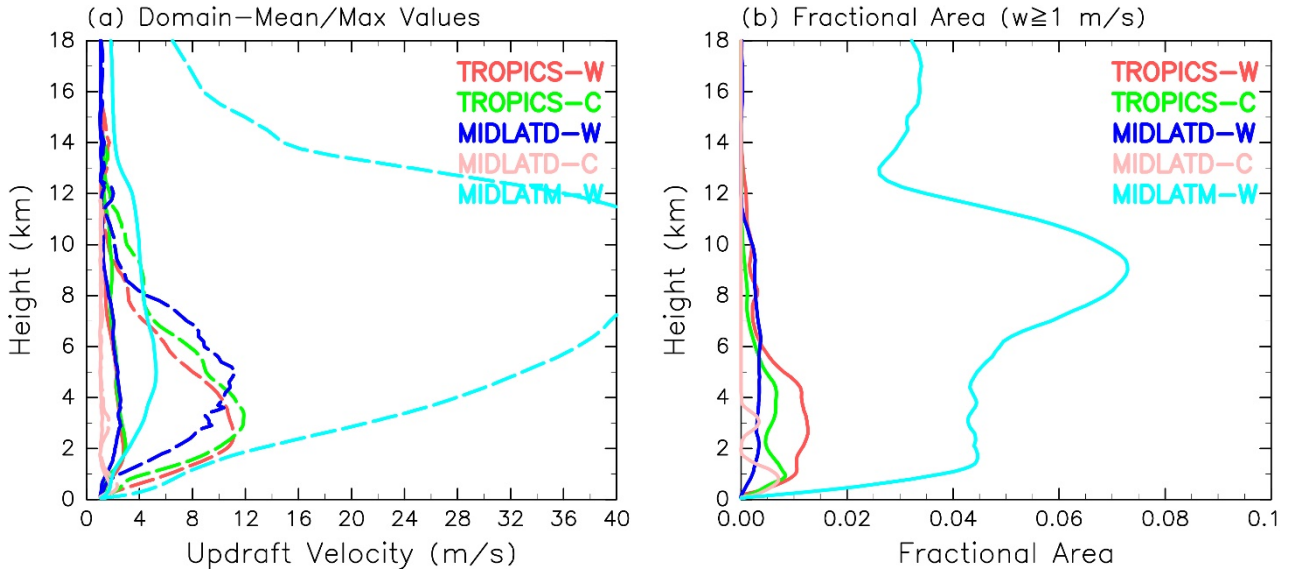


Figure 5. The same as Figure 4, except for the case of the elevated, strong shear (15 m s^{-1} in the 2.5-5 km layer).

The updraft features for all the sensitivity experiments are summarized in Figure 6 for the means and the standard deviations obtained from the time series of the maximum updraft speed within the computational domain. In this figure, the simulated outputs over the whole computational domain from the simulated time period from 2 to 6 hours were used. As seen in Figures 4 and 5, the MIDLATM-W case produced the strongest updrafts among all the stability conditions for all the shear profiles. The maximum updraft is generally stronger in MIDLATD than in TROPICS under the low-level shear conditions; this feature seems to be consistent with the observations of updrafts whose peaks are much higher in the midlatitude than in the tropics (Zipser and LeMone, 1980; Jorgensen and LeMone, 1989; Igau et al., 1999). On the other hand, under the elevated shear conditions, the maximum updrafts in TROPICS are comparable to or slightly greater than those in MIDLATD. As described previously for Figure 5, convection in TROPICS is as active as or more active than that

in MIDLATD, because convection in the midlatitude environments becomes much weaker in MIDLATD than in MIDLATM in the elevated shear.

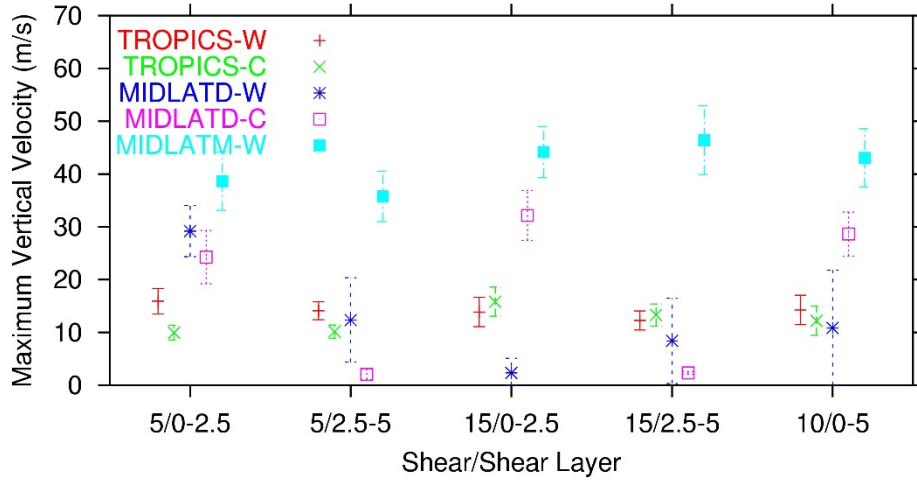


Figure 6. The means (symbols) and standard deviations (bars) of the maximum updraft speed in the computational domain during 2 and 6 hours for all the numerical experiments. Reproduced from Takemi (2014). ©2014 Elsevier. Used with permission.

Figure 7 shows the mean precipitation intensity averaged in space over the computational area and in time during the period from 2 to 6 hours. The standard deviation calculated from the time series of area-mean precipitation intensity is also included in this figure. Note that the spatiotemporal mean precipitation intensity is proportional to the total accumulation of precipitation over the computational area during the specified time frame. Consistent with the features shown in Figures 4 and 5, MIDLATM-W produces the largest amount of precipitation for all the shear cases. On the other extreme, there is virtually no precipitation in the MIDLATD-W condition for every shear profile; furthermore, the lower troposphere is quite dry, and hence precipitation will evaporate before reaching the ground surface. Although the updraft appears to be strong in terms of its peak value, precipitation is not produced correspondingly. It was previously identified that the statistics of maximum updraft and mean precipitation do not necessarily agree with each other (Weisman and Rotunno, 2004).

In the MIDLATD-C case, precipitation is produced if the shear layer is based at the surface. On the other hand, in the TROPICS cases, the sensitivity to the initialization method as seen in the MIDLATD cases is not so significant. Depending on the height and intensity of the shear layer, the mean precipitation in the warm and the cold initialization varies, but the variation in TROPICS is less sensitive to the shear profile, compared with the results in the MIDLATD cases.

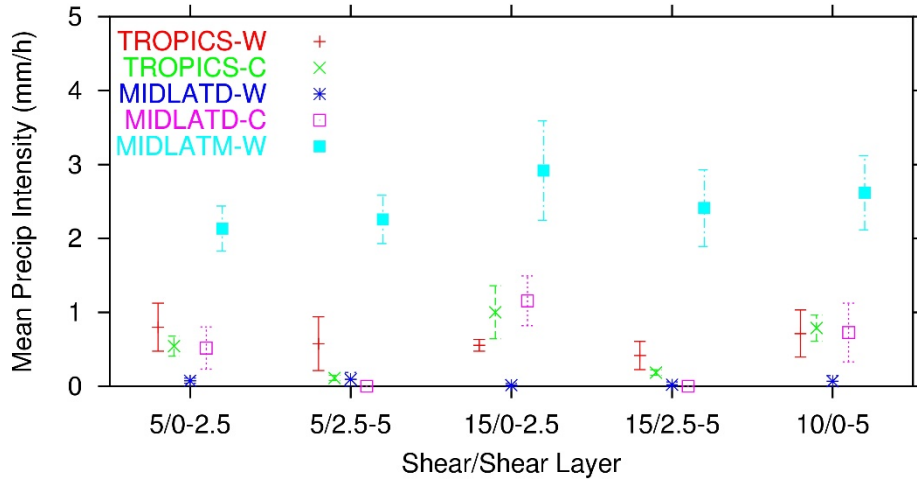


Figure 7. The mean (symbols) and standard deviation (bars) from the time series of spatially averaged precipitation intensity over the computational area during the time period of 2 and 6 hours. Reproduced from Takemi (2014). ©2014 Elsevier. Used with permission.

Takemi (2007a) proposed that the temperature lapse rate in the convectively unstable layer (which basically corresponds to the lower-to-the middle troposphere) well explains the relationship between the squall-line intensity and the stability condition. This lapse rate is written as:

$$\Gamma = -\frac{T(z = z(\theta_{e \min})) - T(z = z(\theta_{e \max}))}{z(\theta_{e \min}) - z(\theta_{e \max})}, \quad (2)$$

where T is temperature, and $z(\theta_{e \min})$ and $z(\theta_{e \max})$ are the heights having the minimum and maximum equivalent potential temperatures, respectively. Note that both $\theta_{e \min}$ and $\theta_{e \max}$ appear within the convectively unstable layer which is below $z(\theta_{e \min})$. With Eq. (2), the lapse rate in the convectively unstable layer is quantified. Takemi (2007b) found that the rainfall amount generated by MCSs scaled well with the lapse rate defined by Eq. (2). Furthermore, the vertical distribution of CAPE for each air parcel that originated at a different height was shown to strongly depend on the temperature lapse rate (Takemi, 2010). In the environment with a smaller lapse rate, the depth having a substantial amount of CAPE becomes shallower even though the CAPE value for the surface-based air parcel is not changed. If the depth having some CAPE values becomes deeper, air parcels not only at the lowest level but also at elevated levels in the lower troposphere will contribute to the upward motion. Updraft enhancement is definitely beneficial for the development of MCSs. The importance of the vertical distribution of CAPE in developing MCSs was emphasized by Takemi and Satomura (2000). They investigated the mechanism for the maintenance of squall lines in a dry environment and found that air parcels at elevated levels in the boundary layer are potentially unstable (i.e., having non-zero CAPE values) with short distances to their levels of free convection (LFCs) and hence are raised easily above LFCs to become convective cells. From a number of sensitivity experiments, Takemi (2010) found that the difference in the buoyancy profile under different temperature lapse rates can be interpreted as the difference in the vertical distribution of CAPE for surface-based and elevated air parcels. The vertical distribution of CAPE was also recognized to play a key role in the development of nocturnal convective systems (Parker, 2008).

3. LINEAR-SHAPED CONVECTIVE SYSTEMS IN A HUMID CONDITION

3.1 Observed Features of Linear-Shaped Convective Systems in Japan

The morphology and environmental properties of MCSs have been widely investigated as described in Section 1. However, most studies have paid attention to cases that occurred over continental, drier/semi-arid climate regions and over tropical oceanic regions. In contrast, less studies have conducted analyses on cases occurred in Asian monsoon regions. The work of Meng et al. (2013), briefly mentioned in Section 1, should be noted as a study examining cases occurred in East Asia. They used 2-year radar data to identify three patterns of the structural evolution of squall lines in east China and found that the squall lines in east China tend to form in a moister environment (and hence a larger amount of precipitable water vapor) with weaker vertical shear than the United States counter-parts like those shown in Bluestein and Jain (1985). They also showed that the largest instability and the most humid environment are seen in the squall lines with leading stratiform regions in east China, which contrast to the cases in the United States where trailing-stratiform-type squall lines display the most unstable and humid condition. The dominance of the leading-stratiform type in China may be due to the influences of synoptic-scale flow patterns such as upper-level trough and cyclonic circulation. In the following, the climatology of linear-shaped convective systems over Japan will be described, as an example of those occurring in humid climate regions.

Climatological analysis on convective systems over Japan was first conducted by Unuma and Takemi (2016b) who examined the composites of operational weather radars throughout the Japanese main islands. Despite anticipated limitation of the spatial coverage over the Japanese land area, long-term dataset for 8 years enabled to detect robust features of mesoscale precipitating systems during warm seasons (i.e., from May to October). Stationary and slow-moving systems were specifically chosen, which were termed as quasi-stationary convective clusters (QSCCs). An automated detection algorithm which was originally developed by Shimizu and Uyeda (2012) to identify an individual convective cell was used to extract QSCCs. To diagnose the environmental conditions for the occurrence of mesoscale precipitating systems, upper-air sounding data observed nearby stations were used. It was found that the typical horizontal scale of QSCCs is about 20 km, indicating that they are meso- β -scale phenomena. The comparison of the environmental conditions between the QSCC and no-rain cases indicated that the relative humidity at low- and middle-levels controls the development of QSCCs; specifically, the QSCCs favorably occur under conditions of higher humidity in the middle troposphere. The study suggests that the middle-tropospheric moistening before the convection development plays an important role in generating QSCCs.

Unuma and Takemi (2016a) further investigated the morphology of QSCCs and found that most QSCCs take a linear shape throughout the areas where QSCCs frequently occur (Figure 8). The comparison of the environmental conditions for linear-shaped and circular-shaped QSCCs shows that CAPE and shear-related parameters are statistically significant in distinguishing the difference in the environmental conditions. Bulk Richardson number, which is a non-dimensional parameter combining CAPE and vertical shear, also separates significantly the environmental difference; the bulk Richardson number for the linear-shaped QSCCs is 32.8, significantly lower than that for the circular QSCCs, and is comparable to the value for the back-building squall lines in the United States (Bluestein and Jain 1985). Considering that the majority of QSCCs takes a linear shape, a mechanism for generating linear-shaped QSCCs is suggested to be a back-building process.

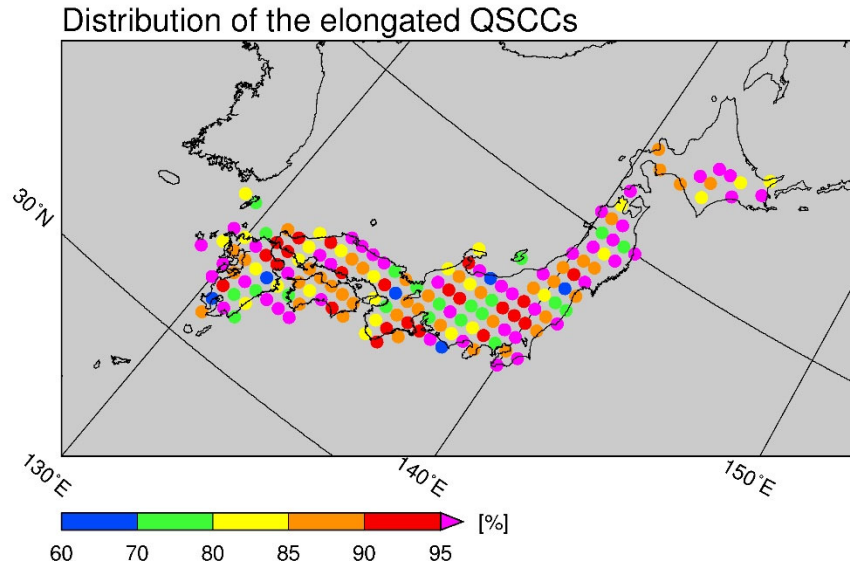


Figure 8. The frequency distribution of the percentage of the number of linear-type quasi-stationary convective clusters to the total number of the quasi-stationary convective clusters over the Japanese islands. Reproduced from Unuma and Takemi (2016b). ©2016 the The Meteorological Society of Japan. Used with permission.

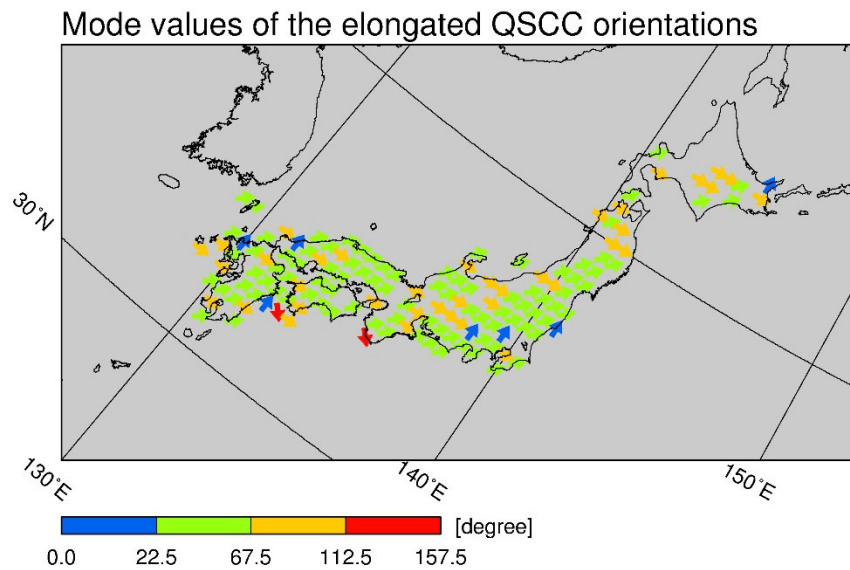


Figure 9. The distribution of the mode values of the orientation angle for the linear-type quasi-stationary convective clusters over the Japanese islands. Reproduced from Unuma and Takemi (2016a). ©2016 the The Meteorological Society of Japan. Used with permission.

The orientation angles of linear-type QSCCs over Japan are demonstrated in Figure 9. Linear-type QSCCs are oriented mostly in the southwest-northeast direction, followed by those oriented in the west-east direction. These dominant directions are determined primarily by monsoonal winds during the summer season in East Asia. In general, propagating squall lines as observed in the continental region of the United States are oriented not so much in the dominant wind direction but rather in the shear direction. On the other hand, the linear-type QSCCs over Japan develop in environments

where directional shear is not so large as in the United States. Therefore, dominant winds like the monsoonal flows affected the orientation of linear QSCCs in Japan.

The research progress and current understanding of stationary precipitating systems over Japan have been recently reviewed in Kato (2020). Special focus was paid to quasi-stationary band-shaped precipitation systems that produced heavy rainfalls (i.e., the total rainfall of 200 mm or greater), termed as “senjo-kousuitai”. Senjo-kousuitai is a Japanese word and its direct translation is linear-shaped precipitation area. The definition of the quasi-stationary band-shaped precipitation systems in Kato (2020) is a banded rainfall area with a length of 50–300 km and a width of 20–50 km, generated by successive development of convective cells within similar areas. Major processes for the formation of such linear precipitation area are a broken-line type and a back-building type similar to those identified for squall lines in the United States (Bluestein and Jain, 1985). Kato (2020) listed 6 conditions favorable for the generation of “senjo-kousuitai”: a larger amount of moisture flux at the 500-m height; short distance of LFC for an air parcel originated at the 500-m height; higher relative humidity at the 700- and 500-hPa levels; higher storm-relative helicity; a larger upward velocity at the 700-hPa level; and higher LNB for a parcel at the 500-m height. A short displacement distance of an air parcel to LFC was found to be a favorable condition for the maintenance of squall lines in dry environments (Takemi and Satomura, 2000), and it is interesting to note that this short displacement toward LFC has been identified as an important factor for the formation of mesoscale precipitating systems also in moist environments. Also pointed out is the importance of moisture at middle levels. Climatological features of quasi-stationary band-shaped precipitation systems were investigated for cases in East Asia, indicating that those stationary precipitating systems contribute significantly to the total rainfall amount in western Japan, the Nansei Islands, and East China Sea (Goto and Satoh, 2022).

In 2010's, a number of extreme rainfall events occurred and spawned severe disasters in Japan. Especially in early July 2017, a heavy rainfall event occurred in northern Kyushu Island, with the total daily rainfall greater than 600 mm in a localized area (Kato et al., 2018; Takemi, 2018), and spawned flooding and landslides in a concentrated region, having significant societal impacts. One year later in the event in early July 2018, heavy rainfalls developed wide areas over the Japanese islands, particularly in the western and central parts of Japan, and flooding, inundation, and landslides caused a large number of human losses and devastating damages to social infrastructures, agriculture, economic activities, etc. In response to these extreme events, a number of studies have been conducted. A part of the outcomes from such studies was briefly summarized in Takemi (2021).

The July 2017 heavy rainfall case is considered to be caused by a typical case of a linear-shaped MCS (Kato et al., 2018; Takemi, 2018). Naka and Takemi (2023) showed that the presence of moist absolutely unstable layer (MAUL) (Bryan and Fritsch, 2000) provides a favorable condition for the rapid development of convection, which was considered to contribute to the intensification of rainfalls. MAUL was shown to be maintained by continuous moisture flux in the lower troposphere. Because MAUL is characterized as having a saturated state, a process that would create a saturated state should be carefully investigated. Figure 10 shows the areas of heavy rainfall and thick MAUL and the west-east and vertical cross section along the 32.9°N latitude. In Figure 10a, it is seen that a deep MAUL appeared at this time and a heavy rainfall of 60 mm or greater developed in the following 3 hours. Figure 10b indicates that relative humidity at the same time with that shown in Figure 10a is seen to gradually increase from the west to the east in the lower troposphere before the development of the heavy rainfall of 60 mm or greater. Besides, the vertical gradient of equivalent potential temperature is generally negative in the lower to middle troposphere. Therefore, if a saturated layer appears within the layer having negative vertical gradient of equivalent potential temperature, the saturated layer becomes MAUL. The flow

pattern shown in Figure 10b seems to be very similar to the conceptual of slab convective overturning in which MAUL is present (Bryan and Fritsch, 2000). Actually, low-level saturated inflow toward MCSs was noted in Kingsmill and House (1999). Such view is considered to lead to concepts of layer lifting (Mechem et al., 2002) and slabular convection (James et al., 2005). The presence of MAUL is considered to enhance convective motion and hence contribute to the organization and evolution of MCSs. Moistening processes of the lower to middle troposphere is important to understand mechanisms for the formation and maintenance of MAUL and the impact of MAUL in intensifying convection through, for example, layer lifting or slab overturning.

In the followings, the numerical modeling of the July 2017 event will be described.

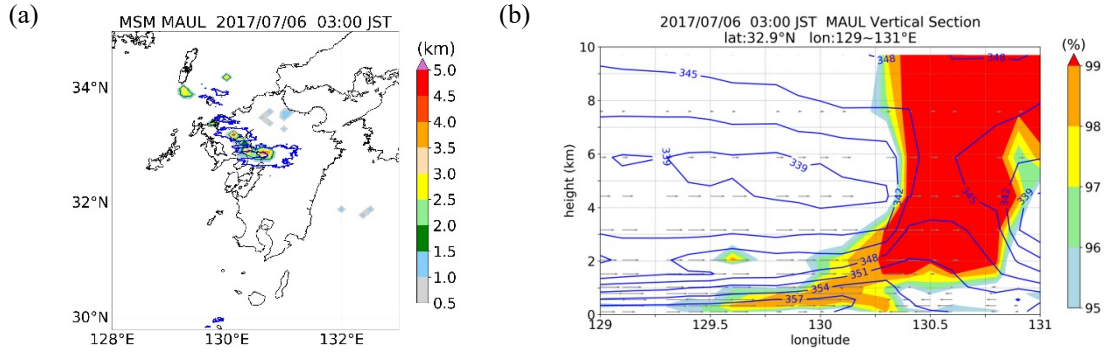


Figure 10. (a) The horizontal distribution of the thickness of the MAUL (in km, color shading) and the accumulated rainfall of 60 mm for the 3 h afterward (blue contour) in the area around Kyushu at 1800 UTC 5 July 2017. Reproduced from Naka and Takemi (2023). ©The Author(s). Published by the Meteorological Society of Japan under a Creative Commons Attribution 4.0 International (CC BY 4.0) license. (b) The vertical cross section of relative humidity (color shading), equivalent potential temperature, and winds vectors projected on this section along the 32.9°N latitude.

3.2 High-Resolution Modeling of Linear-Shaped Convective Systems: A Case Study

In this subsection, a heavy rainfall case that occurred in northern Kyushu, Japan on 5-7 July 2017, referred to as the July 2017 Northern Kyushu Heavy Rainfall event, was chosen. This case produced extreme rainfalls concentrated in a limited region in northern Kyushu and spawned damaging floods and landslides. This case has recently been investigated by Kato et al. (2018), Takemi (2018), Kawano and Kawamura (2020), Tsuji et al. (2020), Ito et al. (2021), Nayak and Takemi (2021), Unuma and Takemi (2021), and Sato et al. (2022). Here we focus on the high-resolution modeling of a linear-shaped stationary MCS by precisely representing a complex and complicated topography in numerical simulations.

Takemi (2018) conducted convection-resolving simulations of a linear-shaped stationary MCS that generated the July 2017 Northern Kyushu Heavy Rainfall in order to examine whether a numerical simulation is able to represent the stationarity of the extreme-rain-producing convective system and to quantitatively reproduce the extreme amount of rainfall. The numerical model used was the WRF/ARW model, version 3.6.1 (Skamarock et al. 2008). The physics parameterizations used in the numerical simulations were a double-moment cloud microphysics scheme for cloud and precipitation processes (Morrison et al., 2009), the Yonsei University scheme for boundary-layer mixing (Hong et al., 2006), a Monin-Obukhov similarity-based scheme for surface fluxes (Jimenez et al., 2012), and the RRTMG scheme for

short-wave and long-wave radiation (Iacono et al., 2008). No cumulus parameterization was used. The two-way nesting technique was employed in order to cover a large domain including the Japanese islands and to resolve convective motion and complex topography at a sufficient resolution. We set four computational domains: the outermost domain (Domain 1) covers most of the Japanese islands and the surrounding regions within the area of 2025 km by 2025 km at the 4.5-km horizontal grid spacing under the Lambert conformal projection on the plane crossing the latitudes of 30°N and 60°N, the second domain (Domain 2) Kyushu Island in the area of 450 km by 450 km at the 1.5-km grid, the third domain (Domain 3) the northern half of Kyushu Island in the 220 km by 200 km area at the 500-m grid, and the innermost domain (Domain 4) focuses northern Kyushu in the area of $(100 \text{ km})^2$ at the 167-m grid (Figure 11). In the domains having the horizontal grid spacing of 500 m (Domain 3) and 167 m (Domain 4), the model topography was generated with the use of a high-resolution digital elevation model (DEM) dataset having a 50-m resolution available from the Geospatial Information Authority of Japan (GSI) to reproduce precisely a complex and complicated feature of the topography in the region. Figure 12 exhibits the difference in the elevation of the model topography generated from the 50-m resolution DEM data of GSI and generated from the global 30-second data, GTOPO30, of the United States Geological Survey (USGS). It is clearly indicated that the higher and lower elevations in the domain are represented higher and lower, respectively, in the case of GSI DEM data than in the case of the USGS data, suggesting that detailed features of the complex topography in the region are represented more precisely in the GSI DEM data than in the USGS data. In other words, the topography generated with the USGS data are smoothly represented.

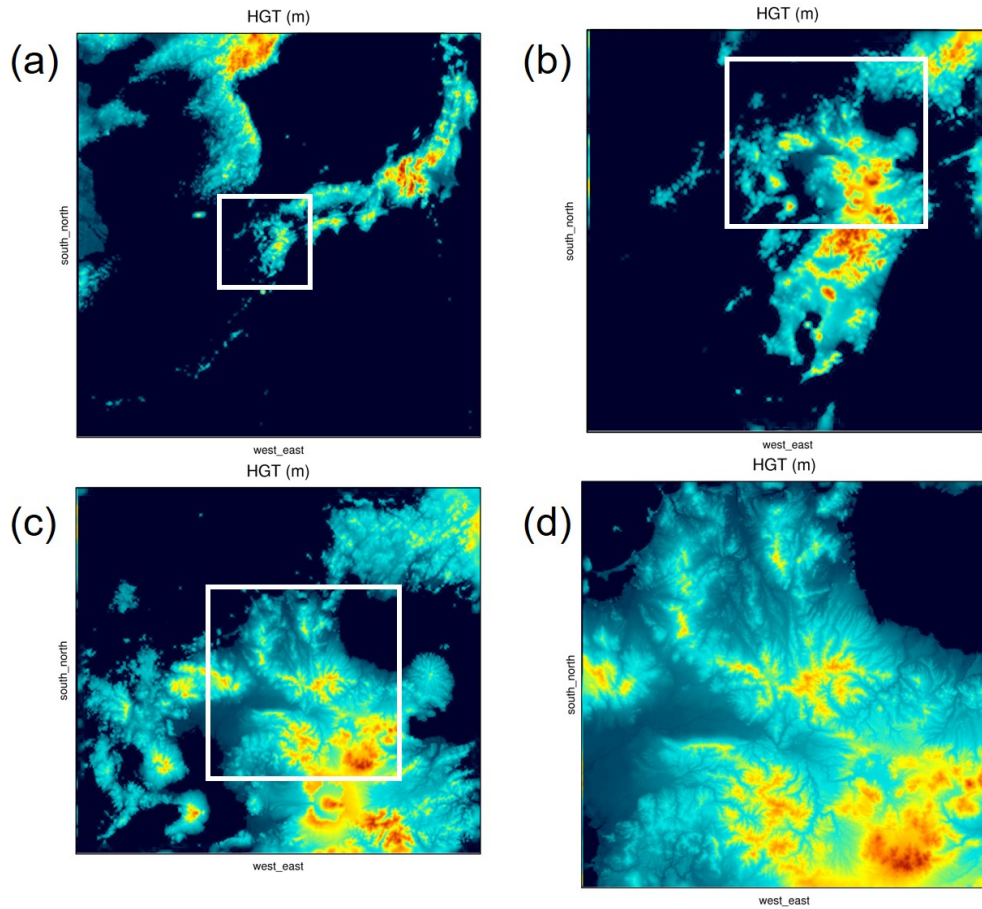


Figure 11. The domain configurations of the numerical experiments: (a) Domain 1, (b) Domain 2, (c) Domain 3, and (d) Domain 4. Note that the color shading is scaled with the minimum and maximum terrain heights in each domain.

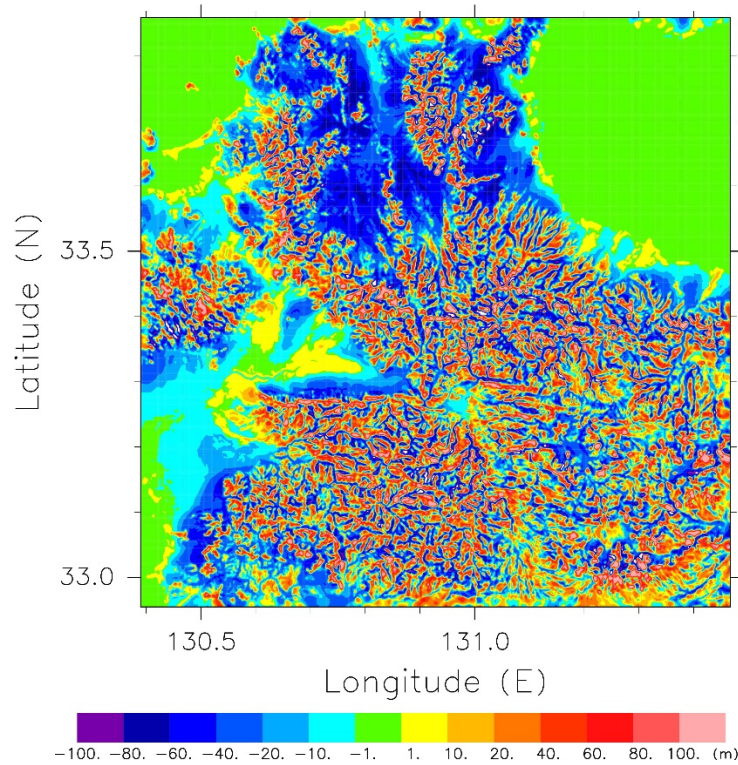


Figure 12. The difference of the surface elevation height (m) generated from the GSI from that generated from the G30 DEM data in Domain 4. Reproduced from Takemi (2018). ©The Author(s). Published by the Meteorological Society of Japan under a Creative Commons Attribution 4.0 International (CC BY 4.0) license.

Figure 13 shows the simulated radar reflectivity at the 2-km height in Domain 4 from 0600 UTC to 0900 UTC on 5 July 2017, which well reproduced the observed radar reflectivity (Takemi 2018). Around the center of the domain, a linear-shaped MCS oriented in the east-west direction, indicated by areas of strong radar reflectivity, is reproduced. The linear MCS seems to be stagnated in a similar area. From the simulated fields, it was found that individual convective cells continuously developed in the western part of the linear rainfall area and moved eastward. This process is regarded as a back-building type in the definition of Bluestein and Jain (1985). The successive development of convective cells kept the precipitating system stationary and generated strong rainfalls in the same area, resulting in a linear-shaped area of extreme rainfall.

As a result of the successive development of convective cells and the formation of a linear-shaped stationary precipitating system, the accumulated rainfall exceeds 600 mm (Figure 14a). Among the raingauge stations in northern Kyushu, the heaviest rainfall was measured at the Asakura station: the maximum accumulated rainfalls for 24, 48, and 72 hours were 545.5 mm (by 1140 JST 6 July), 600.5 mm (by 1040 JST 7 July), and 616.0 mm (by 0600 JST 7 July), respectively. Although there is a slight difference in the exact location of the heavy rainfall of the simulation compared with the observation, the area with over 500 mm rainfall in the simulation extends longitudinally, and the pointwise maximum rainfall in the simulation amounts to 633 mm. In this way, the performance of the 167-m-resolution simulation is highly evaluated in representing the observed features of the back-building, linear-shaped MCS and the resulting linear-shaped heavy rainfall area.

Figure 14 further compares the representation of the total rainfall amount in the simulations with the GSI 50-m-mesh

DEM data and with the GTOPO30 data. The simulation with the GTOPO30 terrain (Figure 14b) indicates the total rainfall amount of at most 400 mm and a smoothed rainfall area, compared to the simulation with the GSI terrain (Figure 14a). Takemi (2018) indicated that this reduced rainfall amount in the simulation with the GTOPO30 terrain is due to weaker low-level forcing in this simulation than in the simulation with the GSI terrain and is also due to a more propagating feature of convective clouds in the simulation with the GTOPO30 terrain. Thus, it is clearly indicated that the decreased frequency of stronger rains and the less stationarity of the convective system make the accumulated rainfall in the limited region smaller. As Yoshizaki (2000) showed that even small and low mountains are able to generate an organized rainband under a moist convectively unstable condition, the present analysis shown in Figure 14 emphasizes a possible role of fine-scale terrain features in generating and maintaining stationary MCSs and hence leading to a concentrated area of rainfall.

The impact of the fine-scale terrain representation on the simulation of rainfall amount is further examined by focusing on how the two-way-nested inner domains quantitatively affect the rainfall. For this purpose, we conducted three additional numerical experiments in which inner computational domains were excluded: 1) Domain 4 was excluded; 2) Domain 3 and 4 were excluded; and 3) Domain 2, 3, and 4 were excluded. In these sensitivity experiments, the model topography in Domain 3 was generated with the use of the GSI's 50-m-mesh DEM data. The rainfall distributions in the area corresponding to the Domain 4 size when Domain 4, Domain 3-4, and Domain 2-4 are excluded are shown in Figures 15a, 15b, and 15c, respectively. With the 500-m resolution (Figure 15a), the rainfall is seen to be concentrated around the center of the domain, similar to the feature shown in Figure 14a but generally reduced. In comparison to the rainfall shown in Figure 14b, a larger amount of rainfall is reproduced in Figure 15a, which suggests that a higher-resolution terrain dataset has an advantage in quantitatively representing the rainfall amount. With the resolution reduced to 1.5 km (Figure 15b) and 4.5 km (Figure 15c), the total rainfall becomes significantly smaller and the linearshaped feature of the rainfall area is lost. The features shown in Figure 15 strongly support the importance of the terrain representation.

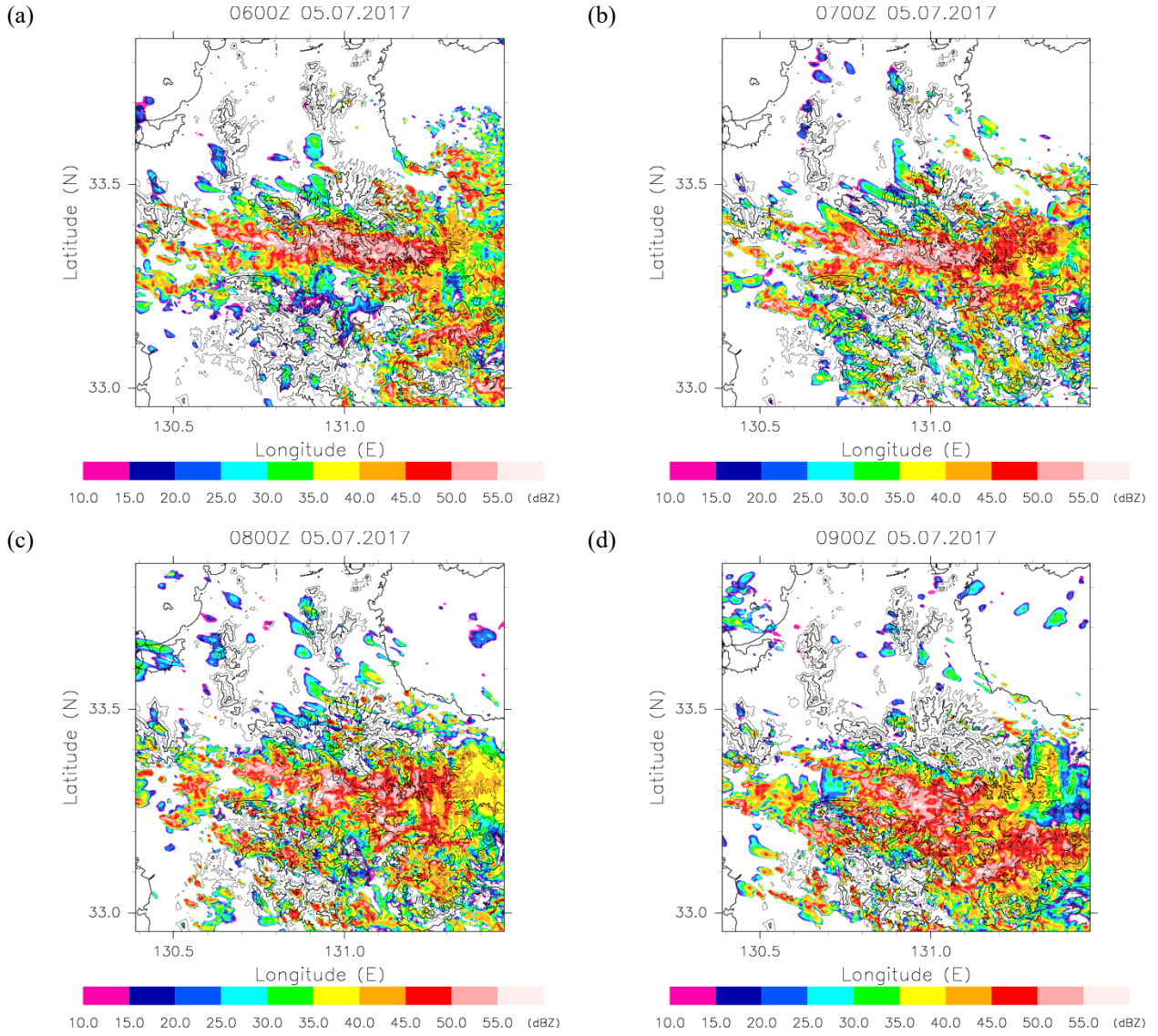


Figure 13. The simulated radar reflectivity field at the 2-km height in Domain 4 at (a) 0600 UTC, (b) 0700 UTC, (c) 0800 UTC, and (d) 0900 UTC on 5 July 2017.

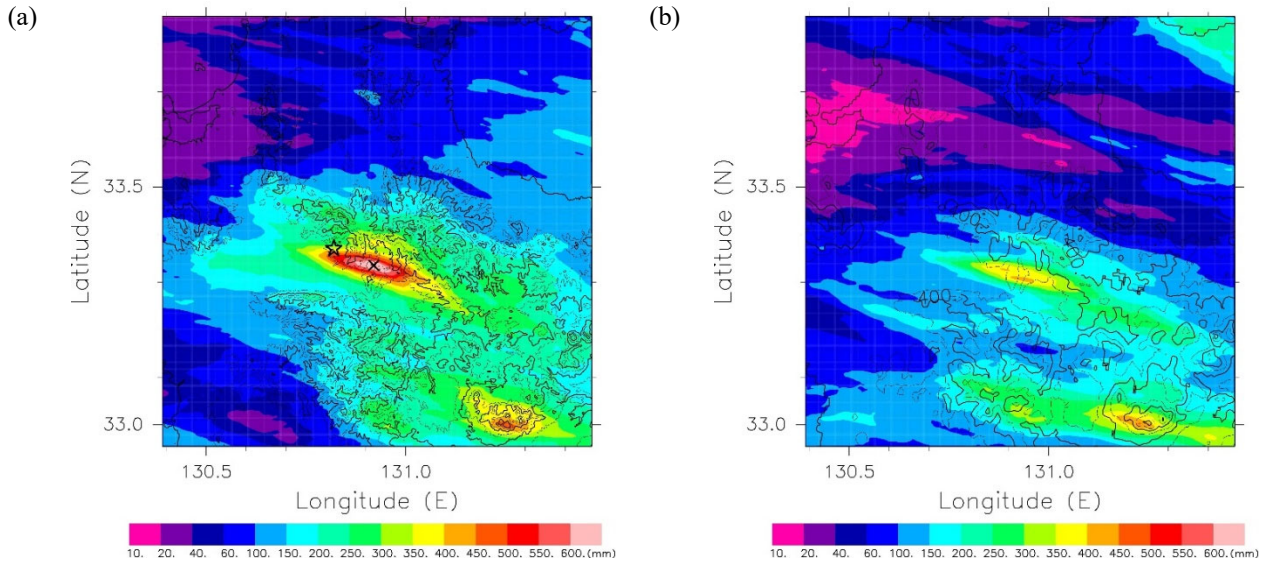


Figure 14. The accumulated rainfall from 0300 JST 5 July to 0900 JST 7 July 2017 in Domain 4 simulated in the experiment with the topography generated from (a) the GSI's 50-m-mesh DEM data and (b) the GTOPO30 data. In (a), the contour lines indicate the surface elevation at the 200-m interval, and the star and the cross marks denote the locations of the Asakura grid point and the point of the maximum accumulated rainfall, respectively. Reproduced from Takemi (2018). ©The Author(s). Published by the Meteorological Society of Japan under a Creative Commons Attribution 4.0 International (CC BY 4.0) license.

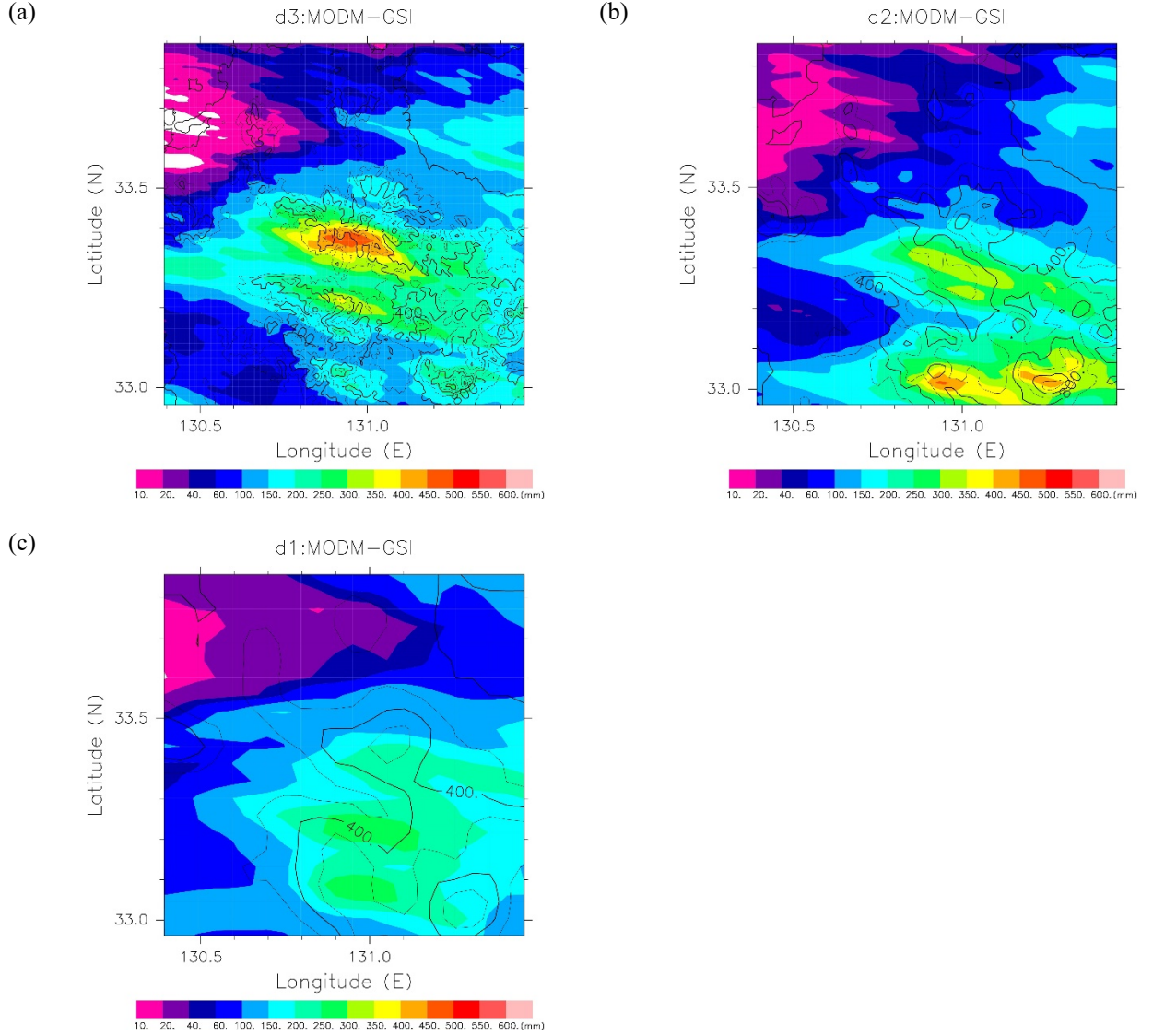


Figure 15. The accumulated rainfall from 0300 JST 5 July to 0900 JST 7 July 2017 simulated (a) with Domain 4 excluded, (b) with Domain 3 and 4 excluded, and (c) with Domain 2, 3, and 4 excluded.

4. SUMMARY AND CONCLUDING REMARKS

This chapter firstly presented the results of the idealized numerical experiments of squall lines and demonstrated how the tropospheric stability and humidity affect the development and intensity of squall lines. As discussed in Section 2.1, the idea in focusing on the stability condition, i.e. temperature lapse rate, is that the magnitude of the positive buoyancy depends on the environmental temperature lapse rate. The buoyancy is generally smaller in the tropical, oceanic environment than in the midlatitude, continental environments. Smaller buoyancy leads to weaker acceleration of updrafts, resulting in weaker convection and hence weaker intensity of MCSs. The numerical experiments clearly indicated that the intensity of updrafts is much weaker in tropical/oceanic squall lines than in midlatitude/continental squall lines. The tropospheric humidity also characterizes how the lower to middle troposphere is unstable from a viewpoint of the vertical

distribution of CAPE whose value is assessed for air parcels originated not only at the surface level but also at elevated levels in the lower troposphere.

We then describe the geographical characteristics of the occurrence of quasi-stationary MCSs over the Japanese islands in the warm season, as an example of the MCSs under humid conditions by using the operational radar network in Japan. From the upper-air sounding data, it was found that the humidity in the middle troposphere well distinguish the environmental properties whether quasi-stationary MCSs develop. Higher humidity at middle levels (i.e., the layer of 700-500 hPa) is favorable for the generation of the MCSs. With a certain amount of vertical shear in the low-to-middle levels, linear-shaped MCSs preferably occur at everywhere over the Japanese islands. A back-building process is regarded as a key mechanism for the maintenance of the linear-shaped MCSs.

Furthermore, high-resolution modeling of a linear-shaped MCS is described. Special attention is paid to the precise reproduction of fine-scale, complex topography in high-resolution simulations. A heavy rainfall case that occurred in the northern part of the Kyushu Island in Japan in early July 2017 was chosen, because this heavy rainfall was shown to be caused by a well-defined, linear-shaped stationary MCS that generated a linear-shaped rainfall area (Kato, 2020). The high-resolution simulation at the horizontal grid spacing of 167 m with the model topography produced by a 50-m-mesh DEM dataset well represents the successive development of convective cells on the upstream side of a linear-shaped MCS and the stationarity of the linear-shaped MCS. Key issues in this high-resolution modeling are to represent more precisely the complex and complicated nature of topography and to explicitly resolve convective motion. In other words, not only resolving convective-scale motions but also representing complex topography is critically important in high-resolution modeling of stationary-type, linearly organized MCSs.

A notable feature for the generation of linear-shaped MCSs in humid environments is a very humid state not only in the lower troposphere but also in the middle-to-upper troposphere. Therefore, the processes leading to such humid conditions should be investigated in more detail. As indicated in Figure 10b, moistening of the middle and upper troposphere will be critically important. A multi-scale analysis of linear-shaped MCSs and their environmental properties is required to reveal mechanisms for the moistening of the free troposphere and the generation of linear-shaped MCSs.

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