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High-Resolution simulations of Heavy-Rain-Producing Mesoscale Convective Systems using Cloud-Resolving models

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सार – पूर्वी एशिया में, भारी-वर्षा करने वाली मेसोस्केल संवहन प्रणाली (MCSs) अक्सर मॉनसून प्रणालियों में विकसित होती हैं जो भीषण बाढ़ और भूस्खलन का कारण बनती हैं। इन्हें समझने और पूर्वानुमान देने के लिए बादल विभेदन मॉडल (CRMs) का उपयोग उच्च-विभेदन सिमुलेशन आवश्यक हैं। त्सुबोकी और लुओ (2020) ने CRMs का उपयोग करते हुए मेसोस्केल संवहन प्रणाली (MCSs) के हाल के अध्ययनों की समीक्षा की और टिप्पणी दी कि CRMs के लिए रेडार प्रेक्षणों का डेटा आमेलन (DA) MCSs के सिमुलेशन और संख्यात्मक मौसम पूर्वानुमान (NWP) के सुधार के लिए आशाजनक है। बादल विभेदन मॉडल (CRMs) का उपयोग करने वाले मेसोस्केल संवहन प्रणाली (MCSs) से लघु अवधि का संख्यात्मक मौसम पूर्वानुमान देने के लिए सीआरएम के लिए रेडार प्रेक्षण का डेटा आमेलन बहुत प्रभावी है। भारी-वर्षा करने वाले मेसोस्केल संवहन प्रणाली (MCSs) के एनडब्ल्यूपी में सुधार के लिए विभिन्न संवहन-पैमाने के डेटा आमेलन विकसित किए गए हैं। त्सुबोकी और लुओ (2020) के बाद, इस शोध पत्र में बादल विभेदन मॉडल, चरणबद्ध सारणी मौसम रेडार और रेडार प्रेक्षणों के डेटा आमेलन का उपयोग करके मेसोस्केल संवहन प्रणाली पर हाल के अध्ययनों का परिचय दिया गया है।

ABSTRACT. In East Asia, heavy-rain-producing mesoscale convective systems (MCSs) often develop in monsoon systems and cause severe floods and landslides. To understand and forecast these high-resolution simulations using cloud-resolving models (CRMs) are necessary. Tsuboki and Luo (2020) reviewed recent studies of MCSs using CRMs and remarked that data assimilation (DA) of radar observations to CRMs is promising for the improvement of simulation and numerical weather prediction (NWP) of MCSs. The DA of radar observations to CRMs is very effective for short-range NWP of MCSs using CRMs. Various convective-scale DAs have been developed to improve the NWP of heavy-rain-producing MCSs. Following Tsuboki and Luo (2020), this paper introduces recent studies on MCS using CRMs, phased array weather radars and DAs of radar observations.

Key words – Mesoscale convective systems (MCSs), Cloud-resolving models (CRMs).

1. Introduction

Monsoon systems are characterized by quasi-persistent rains in East Asia from late spring to early summer, which are referred to as Meiyu in Taiwan and China, Baiu in Japan and Changma in Korea. Shurin (or Akisame) is a similar rainy season from late summer to autumn in Japan. They are characterized by a quasi-stationary front with weak baroclinicity in the lower troposphere. A large amount of water vapor flow is often present along the front and causes heavy-rain-producing mesoscale convective systems (MCSs) around the front. To study and forecast their formation, cloud-resolving models (CRMs) have been developed and applied in various MCS simulations. Tsuboki and Luo (2020) reviewed recent studies of high-resolution simulations of heavy-rain-producing MCSs using CRMs. The purpose of the present study is to update the review of the latest studies on high-resolution simulations of heavy rainfall caused by MCSs in East Asia.

As reviewed by Tsuboki and Luo (2020), most MCS simulations have been performed at a horizontal resolution of 1-4 km. Horizontal resolution is important for simulations of real weather systems, including MCSs and higher resolution yields better results qualitatively and quantitatively (Robers and Lean, 2008). On the other hand, Oizumi *et al.* (2018) performed simulation experiments of a typhoon-induced intense rainband with four different grid spacings (5 km, 2 km, 500 m and 250 m) and two different planetary boundary (PBL) schemes and their results showed that the combination of a horizontal resolution of 500 m and the Deardorff (1980) PBL scheme provided the best forecast of the heavy-rain-producing rainband. The best choice of horizontal resolution and physical scheme may depend on the characteristics of the MCS.

Although the horizontal resolution of CRM is sufficiently high to resolve individual cumulonimbus clouds (for example, 1 or 2 km), some MCSs fail to be simulated by CRMs. In particular, (quasi-)stationary line-shaped MCSs (SL-MCSs) are difficult to simulate, even though they are the most dangerous precipitation systems among the various types of MCS. The SL-MCSs occasionally develop in monsoon systems and cause severe floods and landslides in East Asia. They cause severe disasters every year and have become a major issue in Japan. Tsuboki and Luo (2020) successfully simulated a heavy-rain-producing SL-MCS on 5th July, 2017 in western Japan. Another SL-MCS resulted in a severe disaster in northern Kyushu on the same day and near the western Japan SL-MCS, but it was difficult to forecast. Recently, Takemi (2018) succeeded in quantitatively simulating the Kyushu SL-MCS using high-resolution CRM with detailed terrain data. The Japan Meteorological Agency (JMA) began forecasting heavy rainfall caused by SL-MCS-type weather systems in June 2022. However, the hit rate of the forecast was very low and the missing rate was significantly high. These results indicate the high difficulty in forecasting SL-MCSs.

These deficiencies in MCS forecasts suggest that some heavy rainfall events are successfully simulated using high-resolution CRMs, while other heavy rainfall systems are difficult to simulate using CRMs. Some factors may be associated with the difficulty of quantitative simulations. A promising method to solve this problem is the assimilation of radar data. Recently, a phased array weather radar (PAWR) has been developed, which can enable rapid three-dimensional observation. Moreover, a polarimetric PAWR has been developed and used for the experimental observations. These state-of-the-art radars are used for data assimilation (DA) and are expected to be promising techniques for convective-scale short-range numerical weather prediction (NWP). Following Tsuboki and Luo (2020), this paper summarizes recent studies of MCS using CRMs, PAWRs and DAs of radar observations and indicates the possibility of improving simulations of heavy-rain-producing MCSs by CRMs and convective-scale DAs.

2. Cloud-resolving models

A possible definition of CRM may be given by the non-hydrostatic buoyancy term, which is composed of deviations of temperature, pressure and water vapor mixing ratio, as well as hydrometeor mixing ratios. CRMs are defined as numerical models that explicitly calculate the time-dependent prognostic equations of all these terms. If the temperature and pressure terms are prognostic while the hydrometeor terms are diagnostic, the model may be referred to as a convection-permitting model (CPM). However, in the literature, CRM and CPM are often used with almost the same meaning.

CRMs have been developed in different countries and are used in the research and operational forecasts of MCSs. Tsuboki and Luo (2020) reviewed MCS studies using the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5) (Grell *et al*., 1994), Weather Research and Forecasting (WRF) (Skamarock *et al*., 2008), Japan Meteorological Agency Non-Hydrostatic Model (JMA-NHM) (Saito *et al*., 2006, 2007), Mesoscale Atmospheric Regional Model for South China (MARS) (Zhang *et al*., 2016) based on the Global/Regional Assimilation and Prediction System (GRAPES) (Xue, 2004; Xue and Liu, 2007) and Cloud Resolving Storm Simulator (CReSS) (Tsuboki and Sakakibara, 2002, 2007; Tsuboki, 2008).

These CRMs are regional nonhydrostatic numerical models. Their basic equations are non-hydrostatic and compressible equation systems. The horizontal coordinates are of the orthogonal curvilinear type, including longitude-latitude coordinates. A finite difference scheme is used for spatial discretization. A staggered grid setting of the Arakawa C-grid is often used in the horizontal coordinate. To consider the effect of orography, a terrain-following vertical coordinate is usually used in CRMs. A staggered grid setting in the vertical coordinate is the Lorenz grid or Charney-Philips grid. A stretching technique is often used in the vertical coordinate to calculate lower levels with fine grid spacing. Because the basic equations include sound waves, CRMs usually use the mode-splitting technique (Klemp and Wilhelmson, 1978) for time integration. Important prognostic variables are the three-dimensional velocity components, perturbations of pressure and potential temperature, water vapor mixing ratio, subgrid-scale turbulent kinetic energy (TKE) and mixing ratios of cloud microphysical variables in the single-moment scheme. In the double-moment scheme of microphysics, the number concentrations of hydrometeors are also calculated simultaneously.

Most CRMs use cold rain bulk parameterizations based on several sources (Lin *et al*., 1983; Cotton *et al*., 1986; Murakami, 1990; Ikawa and Saito, 1991 and Murakami *et al*., 1994; Hong *et al*., 2004 and Hong and Lim, 2006). Subgrid-scale motions are parameterized by, for example, the one-order closure of Smagorinsky (1963) or the 1.5-order closure with TKE (Deardorff, 1980).

Fluxes of heat, moisture and momentum at the Earth's surface are calculated using bulk schemes. Cumulus parameterization is usually not used when the horizontal resolution is sufficiently small to resolve convection. A simple land surface model is a one-dimensional conductivity model. It can include more complicated processes such as land use (vegetation), soil drainage and runoff.

3. Radar observations

Synoptic-scale observations are too coarse to provide information of MCS for the DAs of the NWP. Although the horizontal resolution of CRM is sufficiently high to resolve MCS, it is usually difficult to simulate MCSs if the information of MCSs is not included in the initial field of NWP. Radar observations are effective in providing information on the location and timing of MCS in CRM simulations. A conventional radar is a parabolic antenna type that takes 5-15 min to perform a volume scan. This time interval of observation is sometimes insufficient to capture the rapid development of MCS. A sector scan observes a limited area of observation range in a few minutes and is one method to solve the problem of coarse time resolution of observation. The total elevation steps of conventional radar are usually 15 lower than approximately 40° in elevation, which are not sufficient number of step to determine the detailed vertical structure of the precipitation system.

Explosively developing MCSs have often been observed during the warm seasons in Japan. To observe their detailed time evolution and provide information on their location and time of development, two X-band PAWRs were implemented in Japan in 2014. A broad radar beam of 5°-10° in the vertical and 1° in the horizontal direction is transmitted from 24 antenna elements of the PAWRs and 100 sharp beams of the back-scattering signal are obtained using a digital beam forming technique (Yoshikawa *et al*., 2013). The elevation of the observation ranges from 0° to 90° with an elevation resolution of 1°. The PAWRs are rotated horizontally and one volume scan was performed every 30 s.

Since, the pioneering work of Byers and Braham (1949), the concept of cells has been used to describe convective storms. Using the rapid scanning ability of PAWRs, a more detailed structure and its evolution can be found in convective storms such as MCSs and their high temporal information can be provided to CRMs. Moroda *et al*. (2021) demonstrated the evolution of the precipitation core in a cell using two PAWRs. Moroda *et al*. (2022) utilized two PAWRs to study the relationship between precipitation cores and lightning activity in the upper part of a convective cell, which is called a lightning bubble (LB) (Ushio *et al*., 2003). The rapid scan of the PAWR enabled them to reveal that the upward development of lightning activity corresponded to core evolution.

Recently, a polarimetric PAWR has been developed and operated in Japan (Takahashi *et al*., 2019). It can provide multiple parameters of radar observation and hydrometeor information can be derived from the observation, radar reflectivity and Doppler velocity data. Polarimetric PAWR is expected to provide more detailed information on MCSs to CRMs.

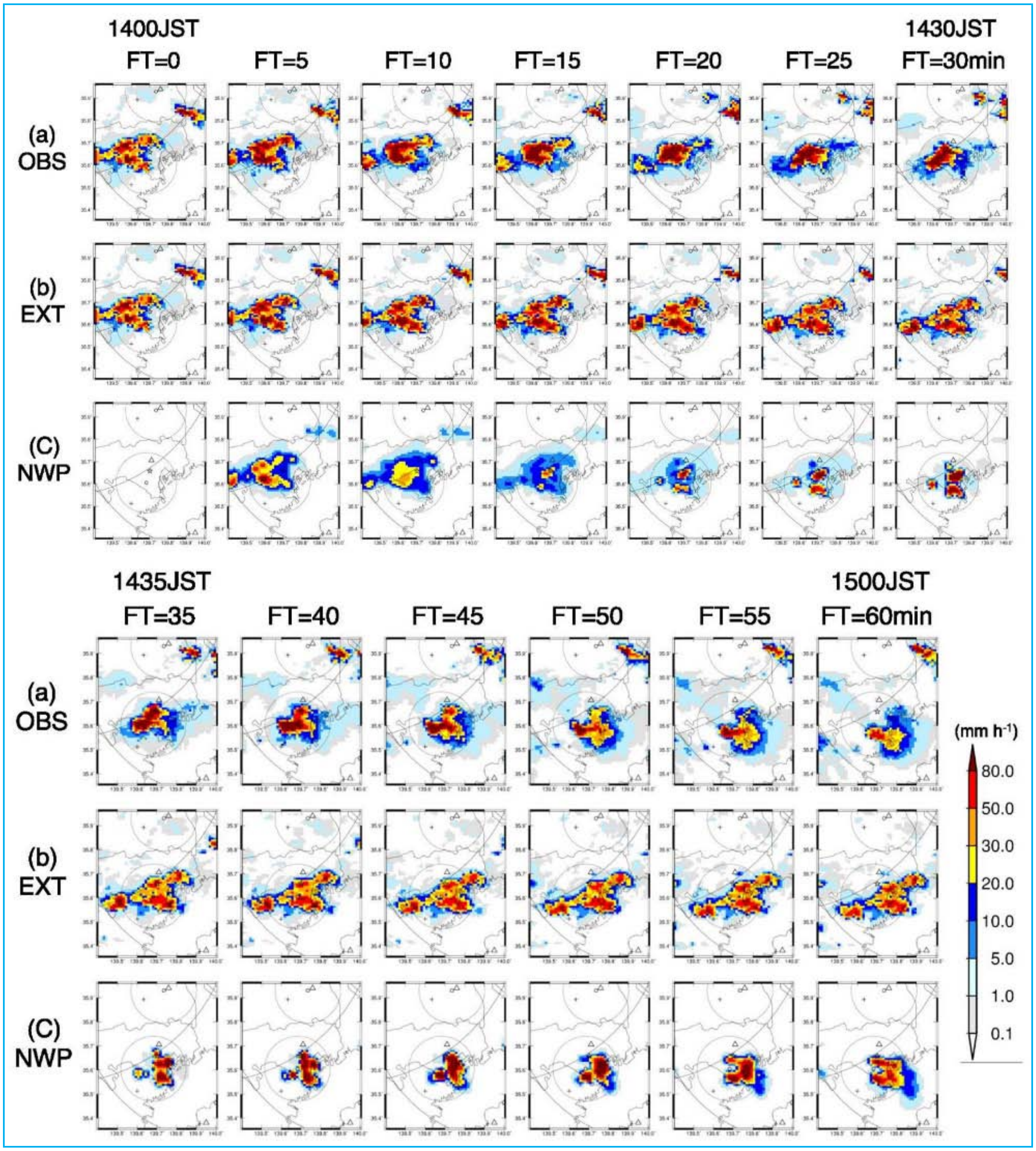
4. Assimilation of radar data

Data assimilation is a key technique for incorporating observation data into NWP and has been used in various scale models from a global scale to storm-scale models. The main DA techniques include the ensemble Kalman filter (EnKF), three-dimensional variational method (3DVAR) and four-dimensional variational method (4DVAR). Although DA research has a wide range and variety in NWP, this review focuses on storm-scale or convective-scale DA because it is closely related to heavy-rain-producing MCS forecasts. Among the three main techniques, we first focus on the 3DVAR technique because it requires a lower computational cost than EnKF and 4DVAR. For the application of real-time NWP at storm-scale or convective-scale, 3DVAR is useful because of its lower computational cost.

4.1. *CReSS-3DVAR*

Recently, extremely intense rainfallhas often occurred around the late Baiu season in Japan. Some of them are caused by SL-MCSs, while others are highly localized rainfall events of meso-gamma-scale (2-20 km in horizontal) MCSs. The latter events occasionally result in flash floods in urban areas. Radar observations provide useful information and the extrapolation of the radar reflectivity distribution is used for very short-range rainfall forecasting. However, extrapolation is limited to less than one-hour for an effective rainfall forecast. On the other hand, NWP has a "spin-up problem" for a very short-range forecast shorter than 3-6 h.

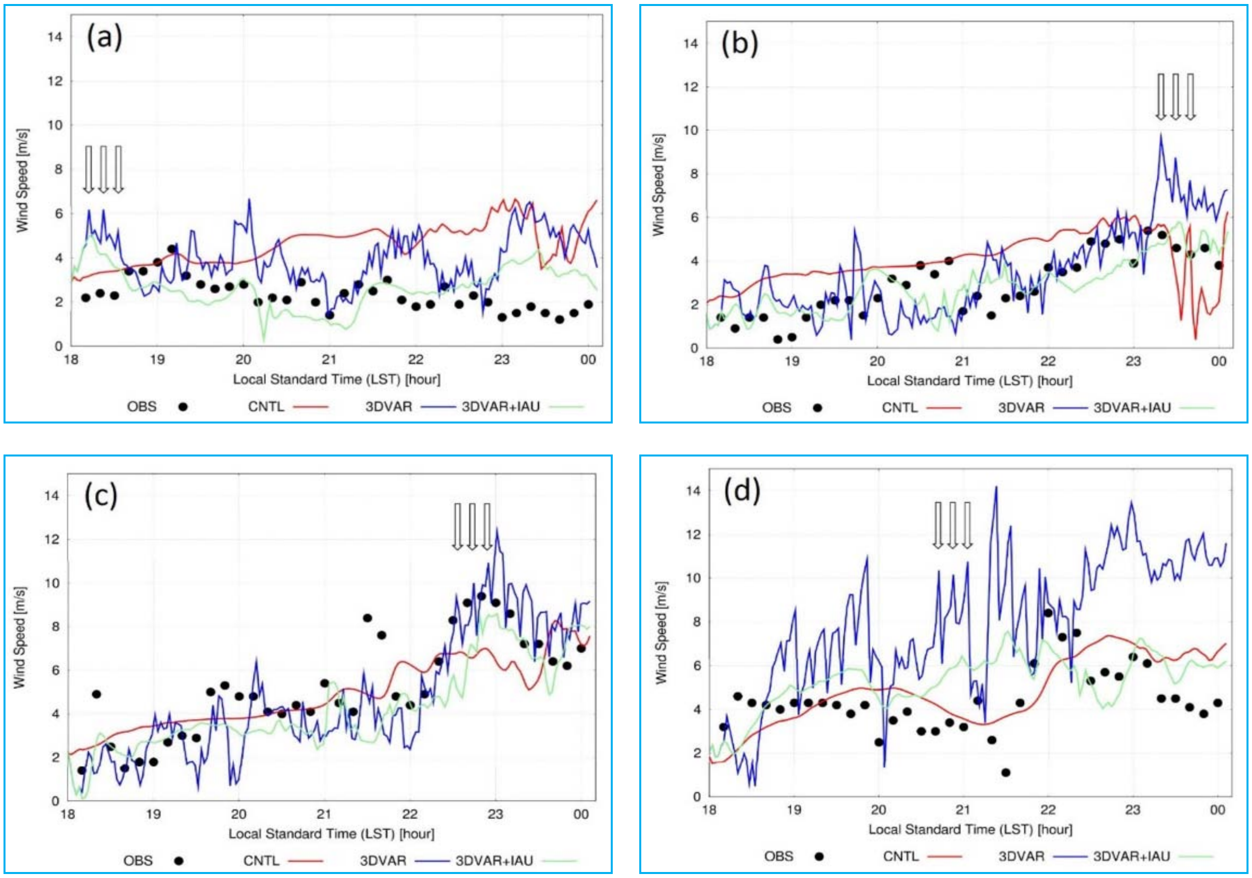
To improve short-range forecasting, blending radar data with NWP is expected to be a promising technique with lower computational cost. Based on the 3DVAR of Barker *et al*. (2004), Kato *et al*. (2017) developed a CReSS-3DVAR forecast system and compared it with the extrapolation of radar data for the extremely heavy rainfall event that occurred in Tokyo, Japan on 24th July, 2015. They assimilated ground-based observations (radars, lidars and microwave radiometers) with a 0.7 km horizontal gird size of the CReSS model. The results



Figs. 1(a-c). Time series of rainfall rate (mm h^{-1}) of the forecast experiments of the heavy rainfall in Tokyo on 24 July 2015. (a) Radar observation, (b) extrapolation of radar data and (c) the NWP using the CReSS-3DVAR (adapted from Kato *et al*., 2017)

showed that intense rainfall was successfully predicted, while the radar extrapolation differed in the rainfall distribution [Figs. 1(a-c)]. They also adjusted the relative humidity in the convective region observed by radar using the vapor adjustment scheme (Wang *et al*., 2013) and found that moisture adjustment is effective for convective-scale forecasts.

The 3DVAR method is effective in improving the convective-scale NWP, whereas an instantaneous 3DVAR causes a discontinuity in the simulation because it usually disturbs the dynamic balance in the model. Shimose *et al*. (2017) found that spike signals appear in the surface wind speed. To suppress such artificial spike-like noise, they applied an incremental analysis update (IAU) with a

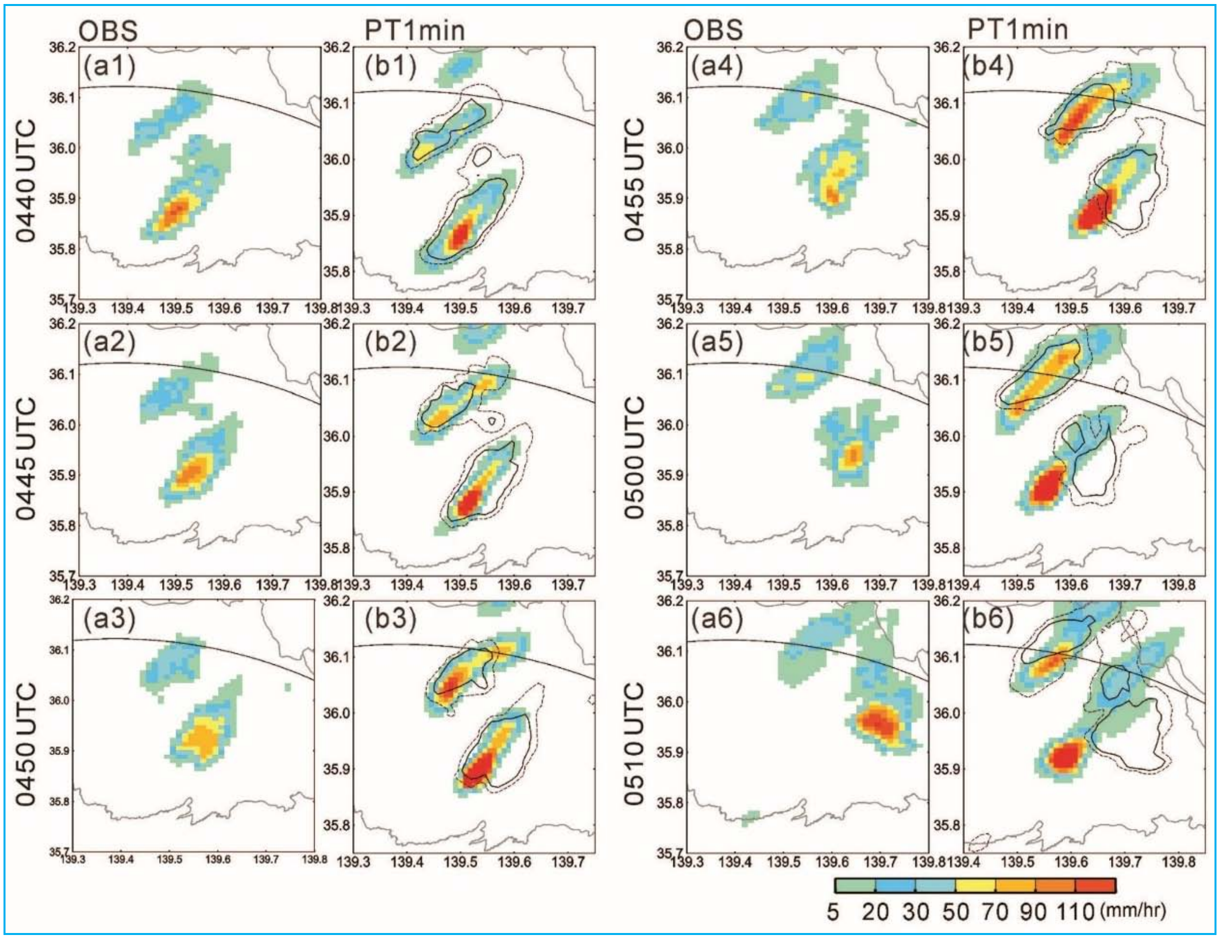


Figs. 2(a-d). Time series of surface wind speed obtained from the NWP experiments on the tornadic storm in Tokyo on 6 September 2015 using CReSS with a horizontal resolution of 500 m at four different places (a-d). The closed circles denote observation, red lines are simulation without DA, blue lines are 3DVAR, green lines are 3DVAR with IAU. The wide arrows indicate representative sharp spike due to the 3DVAR (adapted from Shimose *et al*., 2017)

3DVAR analysis. The IAU technique can relax the shock of instantaneous changes using 3DVAR. In this technique, difference between the first guess of model and the analysis, which is referred to as “increment,” is divided into small pieces and they are added to the first guess during the IAU time window. The IAU with 3DVAR is very effective in convective-scale NWP, particularly for the calculation of high-frequency variables such as the velocity component.

Shimose *et al*. (2017) applied CReSS-3DVAR with the IAU technique to tornadic storms in Tokyo on 6 September 2015. Figs. 2(a-d) shows the time series of the surface wind speed obtained from the simulations without DA, using 3DVAR and 3DVAR with IAU. The spike noise, indicated by the wide arrows, is significant in the 3DVAR simulation (blue lines). In contrast, these spikes were successfully removed in the result of 3DVAR with IAU (green lines) and the simulated wind speed agreed with the observations. This result indicates that the IAU technique is effective for the NWP in highly variable weather systems.

A convective-scale DA is effective for the short-range NWP of MCSs. This requires high-frequency observations of radars that are approximately less than a few minutes. In most DAs using radar observations, reflectivity and Doppler velocity are assimilated in NWP models. Recently, Shimizu *et al*. (2019) demonstrated that thermodynamic variables derived from multiple radar observations are useful for convective-scale DA with a nudging technique. Thermodynamic variables, such as potential temperature and water vapor, are important for the dynamic balance at the convectivescale. They can be retrieved from multiple Doppler observations (Gal-Chen, 1978; Hane *et al*., 1981). Shimizu *et al*. (2019) developed a thermodynamic retrieval method based on Liou *et al*. (2014) and derived the potential temperature from 1-min high-temporal Doppler observations of MCSs. They also used a vapor adjustment scheme (Wang *et al*., 2013) and



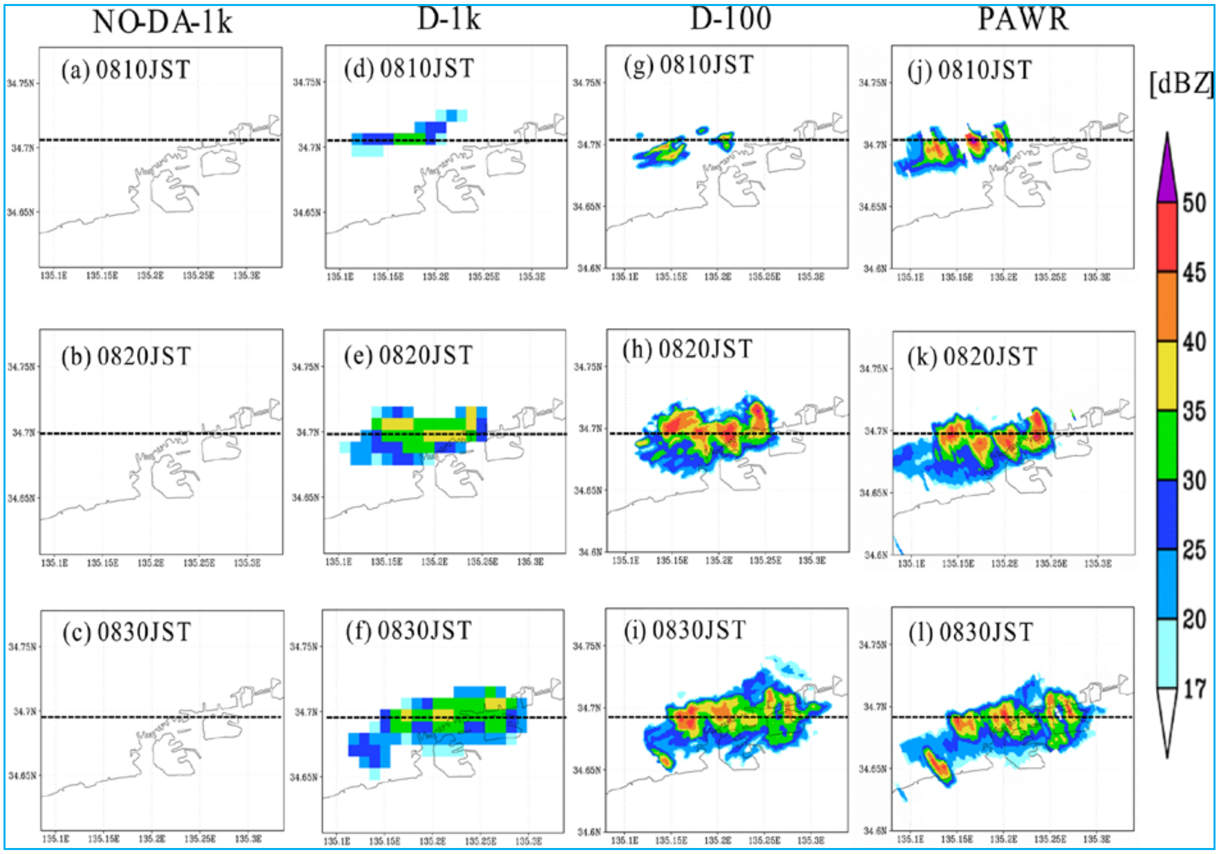
Figs. 3[(a1-a6) & (b1-b6)]. Comparison of radar observations (a1-a6) and the nudging DA experiment (b1-b6) of the tornadic storm observed 0440-0510 UTC, 2nd September, 2013 in Tokyo, Japan every 5 min. Shadings are 5-min averaged rain rate. The thin and thick lines in b1–b6 are observed 5-min rain rate of 5 and 20 mm/h, respectively (adapted from Shimizu *et al*., 2019)

modified the water vapor mixing ratio in convective clouds above the lifting condensation level. The derived potential temperature was assimilated in the 1 km CReSS model with 1-min update using the nudging technique (Stauffer and Seaman, 1994). They applied this technique to a tornadic storm in Tokyo, Japan and showed that the nudging technique provided a better forecast of the storm in the first 30 min {Figs. 3[(a1-a6) & (b1-b6)]}. They also found that a finer temporal resolution of radar observations provides better forecast results according to some sensitive experiments.

Meso-gamma-scale MCS occasionally causes localized heavy rainfall, resulting in flash floods in urban areas. Earlier detection and rapid forecasting are very important for the prevention of disasters due to this type of heavy rainfall. Most convective-scale radar DAs employ precipitation radars (X-band or C-band radars). In contrast, Kato *et al*. (2022) utilized cloud radar (Ka-band) observations for DA of a meso-gamma-scale MCS event. Similar to Shimizu *et al*. (2019), they assumed the saturation of water vapor in convective clouds and utilized the nudging technique (Shimizu *et al*., 2019) to assimilate the water vapor mixing ratio in the 250 m NWP using CReSS. Because cloud radar detects convection before precipitation forms in clouds, earlier information on convection can be assimilated in the NWP. They showed that the heavy rainfall was predicted approximately 20 min after the end of the DA cycle. In the other experiment without radar data DA, precipitation was not predicted. These results indicate that cloud-radar DA with the nudging technique, which requires low computational costs, is highly promising for the NWP of localized heavy rainfall.

4.2. *Local ETKF-Big Data Assimilation*

The above studies are intended for a real-time short-range NWP of MCSs with a small computational cost of



Figs. 4(a-l). Comparison of no-DA experiment (a–c), DA of 1 km resolution (d–f) and DA of 100 m resolution (g–i) with the PAWR observation (j–l) shown in radar reflectivity (dBZ) at 50, 70 and 90 DA cycles of LETKF, which correspond to 0810, 0820 and 0830 JST (adapted from Maejima *et al*., 2017)

storm-scale or convective-scale DAs. On the other hand, DAs for NWP with huge simulations and big data have been developed with the recent rapid development of high-performance large-scale computers. Miyoshi *et al*. (2016) developed a convective-scale NWP with DA utilizing a Japanese 10-petaflops (floating-point operations per second) supercomputer named “K computer” and PAWRs. As mentioned in Section 3, the PAWRs perform full-volume scans in 30s with 100 elevation angles. Miyoshi *et al*. (2016) made a 100-m grid spacing NWP with 30-s update DA. They called this type of DA “Big Data Assimilation” (BDA) and developed a prototype system based on the local ensemble transform Kalman filter (LETKF) (Hunt *et al*., 2007; Miyoshi and Kunii, 2012).

Maejime *et al*. (2017) applied the BDA system to a localized heavy rainfall event that occurred on 11th September, 2014. This event was caused by a rapidly developing MCS, which was observed by PAWRs in Osaka, Japan. They used the JMA-NHM model with LETKF (NHM-LETKF) of 100 ensemble members to assimilate radar reflectivity and Doppler velocity of 30-s PAWR observations. Figs. 4(a-l) compares the results of the 1-km simulation with no DA, 1 km DA, 100 m DA and PAWR observations. The MCS was not simulated with no DA and the 1 km DA experiment was not sufficient to reproduce the detailed structure and rainfall intensity. Comparing 100-DA (Fig. 4i) and PAWRs (Fig. 4l), the 100-m DA successfully reproduced the very detailed structures of convective cells of the MCS and their intensities were comparable to the observations. They demonstrated that the rapid update and high-resolution BDA is highly promising for short-range forecasting in convective-scale NWP.

5. Concluding remarks

Heavy-rain-producing MCSs often develop in monsoon systems and cause severe floods and landslides. Therefore, accurate and quantitative forecasting is necessary for disaster prevention. Because they are composed of intense convective clouds, CRM is indispensable for forecasting. High-resolution simulations using CRMs, such as JMA-NHM, WRF, MM5 and CReSS and successful simulations of heavy rainfall associated with the Baiu front and typhoon. However, some MCSs are still difficult to simulate using CRMs. To overcome this difficulty, DAs of radar observations are promising for the improvement of forecasts using CRMs.

The high temporal resolution of radar observations is very effective for short-range NWP with radar DA, as reviewed in this paper. Recent developments in PAWR, communication infrastructure and high-performance computers have enabled us to perform NWP using CRMs with radar DAs. As summarized in the previous section, there are two streams of short-range NWP that use CRM with a DA. One is the lowcomputational-cost DA, such as 3DVAR and the other is the BDA using LETKF. Both are important and promising for short-range NWP of MCSs. Accurate and quantitative forecasts of MCSs remain a major issue in disaster prevention. In particular, forecasts of SL-MCSs are extremely difficult yet. More intensive development of NWP using CRMs with DA is necessary to improve prediction and understanding of MCSs.

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