Cloud Resolving Simulation of a Local Heavy Rainfall Event on 26 August 2011 Observed in TOMACS

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(Manuscript received 14 December 2016, in final form 13 January 2018)

Abstract

A local heavy rainfall of about 100 mm h\(^{-1}\) occurred in Tokyo and Kanagawa Prefecture on 26 August 2011. This rain was brought by a mesoscale convective system (MCS) that developed near a stationary front that slowly moved southward. In an analysis using geostationary multi-purpose satellite rapid scan images and dense automated weather station networks, development of the MCS occurred after the merging of sea breezes from the east (Kashima-nada) and the south (Tokyo Bay).

Numerical experiments by the Japan Meteorological Agency (JMA) nonhydrostatic model (NHM) with horizontal resolutions of 10 and 2 km using mesoscale 4D-VAR analysis of JMA for initial conditions tended to predict the position of intense rainfall areas west of the observed positions. In the mesoscale ensemble forecast using perturbations from JMA's one-week global ensemble prediction system (EPS) forecast, some ensemble members showed enhanced precipitation around Tokyo, but false precipitation areas appeared north of the Kanto and Hokuriku districts.

As an attempt to improve the model forecast, we modified the model, reducing the lower limit of subgrid deviation of water vapor condensation to diagnose the cloudiness for radiation. In the modified model simulation, surface temperatures around Tokyo increased by about 1°C, and the position of the intense precipitation was improved, but the false precipitation areas in the Hokuriku district were also enhanced in the ensemble member which brought a better forecast than the control run.

We also conducted an ensemble prediction using a singular vector method based on NHM. One of the ensemble members destabilized the lower atmosphere on the windward side of the Kanto district and suppressed the false precipitation in the Hokuriku district, and observed characteristics of the local heavy rainfall were well reproduced by NHM with a horizontal resolution of 2 km.

A conceptual model of the initiation of deep convection by the formation of a low-level convergence zone succeeding merging of the two sea breezes from the east and south is proposed based on observations, previous studies, and numerical simulation results. In this event, the northerly ambient wind played an important role on the occurrence of the local heavy rainfall around Tokyo by suppressing the northward intrusion of the sea breeze from the south.

Keywords TOMACS; local heavy rain; convection initiation; cloud resolving simulation; singular vector; sea breeze

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J-stage Advance Published Date: 11 February 2018

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1. Introduction

Japan experiences multiple disasters, and heavy rainfall is one of the most typical high-impact weather events that lead to meteorological disasters such as flash floods and debris flows. In the past, a quantitative precipitation forecast (QPF) produced by numerical weather prediction (NWP) would have been notoriously bad (Gaudet and Cotton 1988), but recent state-of-the-art NWP models are making heavy rainfalls predictable up to a point if rainfalls occur because of distinct synoptic or orographic forcing, such as orographically forced rain at a typhoon landfall (Saito and Suzuki 2016). On the other hand, it is still difficult for NWP to precisely predict local heavy rainfalls with an effective lead time without strong forcing because of their small spatial and temporal scales. These events usually occur under unstable atmospheric conditions, and their evolution is often sensitive to small perturbations in initial conditions. The number of annual intense rains (e.g., 50 mm h\(^{-1}\)) in Japan has been increasing in recent years because of global warming and urbanization (Kanae et al. 2004; Fujibe 2011).

Initiation of deep convection is the key factor to understanding and predicting thunderstorms and local heavy rainfalls. Several studies going back decades have pointed out the importance of land and sea interfaces in initiating convection over flat terrain (e.g., Neumann 1951; Purdom 1976). The first observational and modeling studies were conducted over the Florida Peninsula (e.g., Pielke 1974; Blanchard and Lopez 1985; Nicholls et al. 1991). Pielke (1974) employed a three-dimensional hydrostatic model to simulate the diurnal evolution of surface convergence over Florida and showed that sea breeze intrusion and the position of the associated convergence zone are strongly affected by ambient wind direction. When the synoptic wind was southwesterly, sea breeze intruded deeper inland from the southwest, and on the northeastern side, a line-shaped convergence zone developed along the coast. Kingsmill (1995) analyzed the initiation of convection associated with a sea breeze front, a gust front, and their collision in east central Florida using satellite, Doppler radar, surface, and rawinsonde data during the Convection and Precipitation/Electrification Project conducted in July and August 1991. The vertical profile of air mass atmospheric conditions between the sea breeze front and the gust front and related convection initiation processes were studied. In this case, convective activity was enhanced by a low-level convergence and upward motion in the air mass between the sea breeze front and the gust front.

Liu and Moncrieff (1996) investigated the effects of ambient wind on density current propagation and morphology using a high resolution two-dimensional nonhydrostatic model. They showed that a headwind (relative flow in the direction opposing the system movement) raised the density current head, and a tailwind had the opposite effect. In a uniform flow, propagation speed was linearly proportional to the ambient wind speed and was reduced or enhanced depending on airflow direction. Inspired by their work, Moncrieff and Liu (1999) used an analytical solution to investigate the role of convergence and wind direction and shear on convection initiation by density currents. They showed that the density current head height is suppressed by surface wind in the windward (tailwind) coast/on-shore flow, but enhanced by surface wind in the leeward (headwind) coast/off-shore flow.

Several field campaigns and numerical experimental approaches to studying convection initiation have been conducted by research communities around the world. A first field campaign targeting the initiation of deep convection over a flat tropical island was the Island Thunderstorm Experiment (ITEX; Keenan et al. 1989, 1990), conducted in the Tiwi Islands (Melville and Bathurst Islands) of Australia’s Northern Territory. During the transition season and breaks in the summer monsoon season, diurnal tropical thunderstorms known as “Hector” that depend on island-scale forcing by sea breezes regularly form. Keenan et al. (1994) classified the convection evolution observed during ITEX into three phases: 1) initial cells, 2) merger and rapid growth phase, and 3) mature squall line phase. Just after the cloud merger, a rapid growth phase occurs, with an abrupt increase of cloud top.

The Maritime Continent Thunderstorm Experiment (MCTEX; Keenan et al. 2000) was a successive international field campaign targeting the initiation of deep convection over the Tiwi Islands. A dense observation network consisting of automatic weather stations (AWSs), Doppler radars, rawinsondes, rain gauges, and wind profiler/radio acoustic sounding systems (RASSs) were deployed by international institutions in 1995. Saito et al. (2001) applied the Meteorological Research Institute (MRI) nonhydrostatic model with a horizontal resolution of 1 km to simulate an event on 27 November 1995, doubly nesting with the Bureau of Meteorology’s Regional NWP system. The model notably well reproduced the evolution of convective activities over the islands during the day, including the appearance of Rayleigh–Benard convection and cloud lines along sea breeze fronts and the rapid growth of deep convection after the cloud merger (see Figs. 10,
of 2011 – 2013. On 26 August 2011, a local heavy rain-
fall event occurred in the Tokyo metropolitan area. In
Tokyo and Kanagawa Prefecture, very intense rains of
greater than 90 mm h\(^{-1}\) that inundated several houses
were observed. This heavy rainfall event was caused
by a mesoscale convective system (MCS) triggered
by low-level convergence, and its characteristics were
captured by a dense observation network deployed by
TOMACS. In this paper, we describe the convection
initiation of this event and its simulation using the
Japan Meteorological Agency (JMA) nonhydrostatic
model.

The organization of this paper is as follows. In
Section 2, we briefly review local circulation and
convective initiation over the Kanto Plain and refer to
TOMACS. In Section 3, we describe the local heavy
rainfall event of 26 August 2011 using satellite images
dense surface observations. In Section 4, we
discuss numerical experiments, a JMA nonhydrostatic
model with horizontal resolutions of 10 and 2 km
employed to simulate the convection initiation, and
present results of experiments with modified model
physics on cloud amount evaluation and ensemble
forecasts using different initial perturbation methods.
In Section 5, we discuss low-level convergence and
convective initiation and propose a conceptual model
of evolution of MCS over the Tokyo metropolitan
area. Chapter 6 presents a summary and the conclud-
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2. Convection initiation over the Kanto Plain and
TOMACS

2.1 Brief review of local circulation and convective
initiation over the Kanto Plain

Figure 1 is a geographical map of the southeastern
part of Honshu Island, Japan. A large portion of the
southeastern part of this area is the Kanto Plain, which
surrounds the Tokyo metropolitan area and is the larg-
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the southeast and the mountainous regions to the north
and west share some similarities with those around
Beijing; however, the large difference is the coverage
of the surrounding sea. In the case of Beijing, the
southeast quadrant is the Yellow Sea, whereas in
Tokyo, the Pacific Ocean is to the east and south. The
sea off the east coast of the northern part of the Kanto
Plain is called “Kashima-nada”, and Tokyo and Sagami
bays lie to the south of the Kanto Plain.

Figure 2 shows a typical daily change of surface
wind circulation over the Kanto district every 3 h for
a weak ambient wind case, analyzed by Kawamura

From May to September, thunderstorms often occur
over the Kanto district, which lies in the southeastern
part of the main island (Honshu) of Japan, and asso-
ciated local heavy rainfalls sometimes cause urban
flooding and influence the functioning of urban life. A
field campaign studying convection and the bound-
ary layer, the Tokyo Metropolitan Area Convection
Study (TOMACS; Nakatani et al. 2013, 2015), was
conducted by the National Research Institute for Earth
Science and Disaster Prevention (NIED), MRI, and 12
additional research organizations during the summers
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In the very early morning (a), winds at the coastal areas are in the off-shore direction, i.e., land breezes. In the morning (b), after sunrise, sea breezes and associated sea breeze fronts appear along the coast. At noon (c), sea breezes intrude inland from the east (Kashima-nada) and the south (Tokyo and Sagami bays). Near the mountainous area, other valley winds toward the mountains appear around the foot hill areas. In the afternoon (d), southerly sea breezes and valley winds toward the mountains merge into a unified circulation known as an extended (large scale) sea breeze (Fujibe 1981). From May to September, thunderstorms often occur over the Kanto district. Cumulonimbus clouds typically first develop in the mountainous region in the afternoon and move south-eastward in the late evening, bringing thunderstorms to the Tokyo metropolitan area by midnight. Note that the ambient winds over eastern Japan in the summer are usually weak southerly.

Kondo (1990) applied a three dimensional hydrostatic model to a simulation of the extended sea breeze over the Kanto Plain. In two cases, one with no ambient wind and one with a southwesterly ambient wind of 5 m s$^{-1}$, their simulation succeeded to reproduce two observed characteristics of the extended sea breeze: (1) the extended sea breeze's thickness (1–1.5 km), which was thicker than a typical sea breeze, and (2) the northward shift of wind direction throughout the Kanto Plain in the early afternoon.

Application of a nonhydrostatic model to local circulation in the Kanto area was first given by Saito (1991), where the simulation with a 5-km horizontal grid interval was conducted as a test case for developing the MRI nonhydrostatic model. When the ground temperature was given by a sinusoidal function with a period of 24 h and an amplitude of 10°C, the ground temperature rose about 8.5°C from the initial time at a forecast time (FT) of 4 h, which corresponds to sin($\pi$/3). Additionally, valley winds developed in the mountains, and because of the difference between the sea surface temperature and ground temperature, sea breezes occurred along the coast (Fig. 3a). At FT = 8 h, sea breezes intrude inland and form frontal lines in the plain (Fig. 3b). In the mountains, valley winds further developed and formed a large-scale circulation (extended sea breeze).

Yoshizaki et al. (1998) analyzed the convergence of three types of wind over the Tokyo metropolitan
area for the case of the 10 Aug 1995 thunderstorm, where ambient wind was northerly. The three types of wind are I: southerly warm and humid sea breeze from Tokyo Bay, II: northerly low-level ambient wind, and III: cool and humid sea breeze from the east coast (Kashima-nada). As shown in Fig. 4, these three winds sometimes converge in the southern part of the Kanto Plain, and the position of convergence is called a “triple point”.

Fujibe et al. (2002) analyzed local wind fields preceding the occurrence of short-time heavy summer rainfall in Tokyo for seven years. Twelve of the 16 cases were characterized by an “E-S-type” pattern, where easterly winds blowing from the east coast of the Kanto Plain (Kashima-nada) and southerly winds from the southwestern coast (Tokyo and Sagami bays) converged around Tokyo. A detailed analysis of the Tokyo area revealed the presence of one or more convergence zones with a scale of 10–20 km, corresponding to the subsequent development of radar echoes.

Seko et al. (2007) analyzed the evolution and airflow structure of a thunderstorm event in Kanto on 21 July 1999 (Nerima heavy rainfall event) using data from JMA’s AWS network (AMeDAS; Automated Meteorological Data Acquisition System), GPS-derived precipitable water vapor (GPS-PWV), Doppler radar observations, and results from a numerical simulation by NHM. The thunderstorm developed in a warm and moist region where southerly winds from Tokyo and Sagami bays and northeasterly flow from the northern Kanto Plain converged, and a convective band organized west of the first system.

Kawabata et al. (2007) developed a high resolution

Fig. 3. a) Simulated lowest level (20 m AGL) wind vectors at t = 4 h. The lower right arrow indicates the scale of 4 m s$^{-1}$. b) Same as in a) but for t = 8 h. After Saito (1991).

Fig. 4. Three winds over the Tokyo Metropolitan Area in case of weak northerly ambient wind (10 August 1995). I: Warm and humid sea breeze from Tokyo Bay, II: northerly ambient wind, and III: cool and humid sea breeze from the east coast. Long barbs on the wind arrows indicate 2 m s$^{-1}$. After Yoshizaki et al. (1998).
nonhydrostatic 4D-VAR system based on NHM and applied it to the Nerima heavy rainfall, assimilating Doppler radar radial wind data, GPS-PWV, and surface temperature and wind data with high temporal and spatial resolutions. A surface convergence line of horizontal winds occurred between a southerly sea breeze and northeasterly winds over the Kanto Plain around Nerima. Because the temperature increase over the northern part of the Kanto Plain was suppressed by clouds blocking sunlight, the temperature difference between the convergence line and its northern side became large, and wind convergence was enhanced around Nerima.

Kusaka et al. (2010) studied essential features of local weather when heavy rainfalls occur in the Tokyo metropolitan area for two heavy rainfall events, one that occurred on 2 August 2002 and one that occurred on 10 August 2004. In the case of the August 2002 event, the E-S-type wind system was observed, and surface winds from Kashima-nada and Tokyo and Sagami bays converged over Tokyo before the heavy rainfalls occurred.

Araki et al. (2015) conducted a case study of a local heavy rainfall event that occurred in a situation with weak synoptic forcing in Chiba City (east of Tokyo) on 9 August 2009. The dense surface AWS network of the Atmospheric Environmental Regional Observation System (AEROS) of the Japanese Ministry of Environment revealed that a triple point was formed by two sea breezes from the southeast (Boso) and the south (Tokyo Bay) and the northerly ambient wind near Chiba City about 1.5 h before convection initiation, which triggered deep convection at 1320 JST (see Supplement 1). They carried out an impact test of data assimilation using NHM and its 3D-VAR system to show that dense surface observations capturing the detailed preconvective environment of low-level convergence were necessary to simulate convection initiation.

### 2.2 TOMACS

The Tokyo metropolitan area, an area about 50 km around Tokyo, is the heart of Japan and boasts a population of more than 30 million. This area is covered by dense observations by JMA, MRI, NIED, the Ministry of Land Infrastructure and Transport (MLIT), and the Geospatial Information Authority (GSI) of Japan. The Tokyo Metropolitan Area Convection Study for Extreme Weather Resilient City (TOMACS) was conducted by MRI, NIED, and 12 other research organizations during the summers of 2011–2013. The science plan for international cooperation on TOMACS (Nakatani et al. 2013) was endorsed as the first WWRP RDP project in Japan in 2013, where seven institutions from five countries were involved. In addition to the operational dense observations by JMA, MRI, NIED, MLIT, and GSI, special observation tools such as a microwave radiometer, five GPS stations, scintillometers, disdrometers, and a very high-resolution (3 km) AWS network were employed, and a field campaign to study convection and the boundary layer with an unprecedented dense network was performed (Nakatani et al. 2015; Shoji 2018).

Figure 5 shows the maximum 1-h precipitation in the Kanto district during TOMACS IOPs. In 2011, many heavy rain events (indicated by blue bars)
occurred in August, and in 2013, heavy rains occurred throughout the summer. One of the flagship events in TOMACS IOPs was the local heavy rainfall event in Tokyo and Kanagawa Prefecture on 26 August 2011 (shown by a black arrow symbol in Fig. 5). This paper targets this event, the evolution of which is described in the next section.

3. Local heavy rainfall event over Tokyo and Kanagawa on 26 August 2011

3.1 Synoptic weather and observed precipitation

On 26 August 2011, a local heavy rainfall event occurred in the Tokyo metropolitan area. In Tokyo and Kanagawa Prefecture, very intense rains of over 90 mm h\(^{-1}\) were observed, and several houses (127 in Tokyo\(^1\) and 13 in Kanagawa\(^2\)) were inundated. At Nerima, the western part of Tokyo’s central business district, a 1-h precipitation amount of 90.5 mm was recorded at 1554 JST. This heavy rainfall was caused by an MCS triggered by low-level convergence, and its initiation and evolution were captured by the TOMACS observation network. Figure 6a shows the surface weather map at 0900 JST on 26 August 2011. No significant disturbances are seen over Japan, but a stationary front from a low-pressure system to the east of Hokkaido runs west–southwestward and crosses Honshu. This front slowly moved southward and reached the south of Kanto at 2100 JST (Fig. 6b).

Figure 7 shows hourly precipitation intensity from 1530 JST to 1830 JST indicated by JMA’s operational precipitation nowcast. At 1530 JST (Fig. 7a), a band-shaped weak to moderate rainfall area corresponding to the stationary front was seen in the northern part of the Kanto Plain, and another very intense rain area appears around Tokyo. This intense rainfall area slowly moved southward, and at 1630 JST (Fig. 7b), it brought extremely intense rainfall of more than 80 mm h\(^{-1}\) along the boundary between Tokyo and Kanagawa Prefecture. The band-shaped weak to moderate rainfall area moved southward slightly faster than the small intense rains and reached the central part of the Kanto Plain. At 1730 JST (Fig. 7c), the band-shaped rainfall area caught up and merged with the intense rainfall area, and the maximum rainfall intensity slightly decreased. At 1830 JST (Fig. 7d), the band-shaped rainfall area was in the southern part of the Kanto Plain. Although some intense rains remained along the southern edge of the rainfall band, general rainfall activity was weakened.

Figure 8a shows the JMA precipitation analysis observed 3-h accumulated precipitation for 1500–1800 JST on 26 August. Intense rainfall totals exceeding 50 mm are seen over Tokyo and the eastern part of the Kanagawa Prefecture.

3.2 Satellite image and surface wind circulation

Figure 9 shows hourly visible images from 1000 JST to 1500 JST on 26 August 2011 taken by the Ministry of Transport’s Geostationary Multi-purpose Satellite (MTSAT; Himawari-7). At 1000 JST (upper left), sea breezes appear in the coastal area, but surface
winds are mostly northerly inland (see Supplement 2). On the east coast facing the Pacific Ocean, shallow convective clouds begin to appear. The sea breezes intrude inland over time, and at 1100 JST (upper middle), cloud lines appear along the sea breeze fronts and become most distinct at 1200 JST (upper right). A sea breeze from Kashima-nada rapidly intrudes inland, while the intrusion of sea breezes from Tokyo and Sagami bays is sluggish because of the northerly synoptic wind (Supplement 2 and Fig. 10a). At 1300 JST (lower left), the east–northeasterly sea breeze from Kashima-nada collides with the southerly sea breeze from Tokyo Bay (Supplement 2 and Fig. 10b), and the two cloud lines begin to merge, triggering deep convection east of Tokyo. At 1400 JST (lower middle), deep convection develops over Tokyo and organizes into an MCS. The MCS then slowly moved west–southwestward and brought heavy precipitation around the boundary of Tokyo and Kanagawa Prefecture (lower right; 1500 JST). A special observation with a 10 min interval rapid scan was also conducted by JMA for this event. In the animation, intrusion of sea breezes and development of deep convection over Tokyo triggered by the merging of sea breeze fronts can be more clearly recognized (see Supplement 3).

Figure 10 shows surface winds and temperatures observed by the dense AWS networks from 1200 JST to 1500 JST on 26 August. In addition to AMeDAS, we used AEROS data from the Japanese Ministry of the Environment (“Soramame” in Japanese; http://soramame.taiki.go.jp/) to illustrate this figure. AEROS has been deployed for air quality monitoring, and its largest characteristic is its high density. For wind and temperature, the average horizontal distance between AMeDAS observation points is about 20 km, whereas AEROS observation points are located every 4–5 km in Tokyo and its surrounding areas. Nishi et al. (2015) provided a detailed description and quality validation.

Fig. 7. Hourly precipitation intensity from 1530 JST to 1830 JST. a) 1530 JST, b) 1630 JST, c) 1730 JST, and d) 1830 JST. After the initial values of precipitation nowcast by JMA.
Convergence lines estimated from surface winds (broken lines) at 1200 JST (Fig. 10a) are found northeast of Tokyo and in the southern part of the Kanto Plain along Tokyo and Sagami bays, which coincide well with the positions of cloud lines seen in the satellite image at the same time (upper right of Fig. 9). The surface temperature difference is clear at the sea breeze front in the northeast, whereas the difference is unclear at the sea breeze front in the southern part of the Kanto Plain, probably because of the relatively warm Tokyo and Sagami bay sea surface temperatures. At 1300 JST (Fig. 10b), the sea breeze front from Kashima-nada merges with the sea breeze front north of Tokyo Bay, and a convergence zone forms around the eastern part of Tokyo. The northerly ambient wind is still seen in the western part of the Kanto Plain, and the three winds form a triple point, whose location...
corresponds with the initiation of deep convection that brought heavy precipitation to Tokyo and Kanagawa Prefecture. Another convergence line is seen in the northern part of Boso Peninsula. At 1400 JST (Fig. 10c), northerly synoptic winds over the western part of the Kanto Plain and the two sea breezes from the northeast and south join over Tokyo and begin to form a cyclonic circulation. At 1500 JST (Fig. 10d), a cold pool produced by precipitation develops between Tokyo and Kanagawa Prefecture. Occurrence of tornadoes was not officially detected on 26 August, but a cyclonic rotating cloud below the cumulonimbus cloud was watched by citizens, who uploaded several mobile phone movies to YouTube\(^3\). Saito et al. (2013) analyzed Doppler radar data and pointed out that two mesocyclones appeared and merged over Tokyo. They also described the detailed evolution of surface winds and pressures observed by a very dense (3 km) surface AWS network specially deployed in TOMACS.

The flow pattern indicated in Figs. 9 and 10 shares the same features as the E-S-type sea breeze, but the position of the low-level convergence is slightly different from other cases (see Fig. 4 and Supplement 1).

4. Numerical model experiments

4.1 JMA operational mesoscale model forecast

Figures 8b–d compare forecast results from the mesoscale model (MSM) for the same valid time of 1800 JST 26 August 2011. MSM is a JMA operational nonhydrostatic model (JMA 2013) based on NHM, with a 5-km horizontal grid distance. Figure 8b shows the simulated 3-h accumulated precipitation of MSM’s 18-h forecast from the initial time of 1500 UTC 25 (0000 JST 26) August. No intense rains are seen over the Kanto Plain, except for a few small scattered rain

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\(^3\) e.g., https://www.youtube.com/watch?v=tz4ZPs1rhxs, and https://www.youtube.com/watch?v=jdNeCzwvWco
areas west of Kanto (northeastern part of Shizuoka Prefecture). North of the Kanto district (Hokuriku district), false rains (where rainfall was not observed) were incorrectly predicted. Figures 8c and 8d show MSM’s 15- and 12-h forecasts for the same valid time, respectively. Both forecasts show a very similar tendency to Fig. 8b, where no intense rains occur over the Kanto Plain, except for a few scattered rains west of the Kanto district, and where false rains in the Hokuriku district are persistently predicted by the operational MSM.

The observed intense rains on 26 August 2011 over Tokyo and Kanagawa were not brought by sporadic non-organized convective cells such as those described by Saito et al. (2017), but instead were brought by an MCS with a relatively larger spatial scale. However, JMA’s operational forecast system failed to properly predict their occurrence that day.

4.2 Numerical model and design of experiments

a. Numerical model

To reproduce this local rainfall event, we performed numerical experiments using the JMA NHM (Saito et al. 2006, 2007; Saito 2012) with horizontal resolutions of 10 and 2 km. Hereafter, we call these two NHMs NHM-10 and NHM-2, respectively. NHM-10
covers Japan and its surrounding area with 361 × 289 grid points and 40 levels, and its domain is the same as that of the former MSM operated by JMA until March 2006. NHM-2 covers mainly the southern part of Japan with 800 × 550 grid points and 60 levels, and its domain corresponds with the pre-operational version of JMA’s local forecast model (LFM) before May 2013. As in the operational MSM and LFM, a three-ice-bulk cloud microphysics scheme based on Lin et al. (1983) is used for both NHM-10 and NHM-2, and the modified Kain–Fritsch convective parameterization is employed in NHM-10. Other physical processes of the two models were almost identical to those of MSM and LFM as of 2013 (JMA 2013).

b. Design of experiments

As a first trial, we conducted a simple downscale experiment of NHM-10 and NHM-2 from the operational mesoscale 4D-VAR analysis of JMA at 1200 UTC (2100 JST) 25 August. The lateral boundary condition of NHM-10 was given by the JMA global model (GSM) forecast from 1200 UTC 25 August. NHM-2 is a downscaling of NHM-10 with a 6-h time lag; therefore, the initial condition of NHM-2 is given by the NHM-10 6-h forecast, and the lateral boundary condition of NHM-2 was given by subsequent NHM-10 forecasts with a 3-hourly boundary update.

We also conducted ensemble prediction with 11 members of NHM-10 and NHM-2 using the above downscale forecasts of NHM-10 and NHM-2 as the control run. As for the initial perturbation method, we tested two methods: perturbation from JMA’s one-week EPS (WEP) and the mesoscale model singular vector method (MSV). The details of the two methods are described in Sections 4.2 and 4.3. Lateral boundary perturbations for the NHM-10 EPS were given by forecasts from JMA’s one-week EPS for both WEP and MSV. Duc et al. (2013) gave a verification of the statistical performance of double-nested EPS like WEP.

Figure 11 illustrates the schematic chart of the downscaling and ensemble experiments configured by NHM-10 and NHM-2. Saito et al. (2017) gave an ensemble simulation using a similar EPS for a sporadic convection case over the Kanto Plain (Ishihara 2013) that occurred on 5 August 2008.

4.3 Forecast results of the downscale control run and EPS by WEP

a. Forecast results of the control run

Figure 12 shows 3-h accumulated precipitation for 1500 to 1800 JST 26 August predicted by control runs of NHM-10 and NHM-2 (without perturbations). Figure 12a is the 21-h forecast of NHM-10 from the initial time of 12 UTC (2100 JST) 25 August. Weak to moderate rains are seen over Tokyo, Kanagawa, and the northern part of Chiba. The forecast seems better than that of MSM for the same valid time (Fig. 8b), but rainfall intensity is still much weaker than observations (Fig. 8a). Also, false rains are predicted in the model over the Hokuriku district. Figure 12b is the downscale run by NHM-2 (15-h forecast from initial time of 18 UTC 25 August). Some intense rains develop in the east coastal area of Chiba Prefecture and over the eastern part of Shizuoka Prefecture, but their positions are inconsistent with observations.

b. Ensemble forecast using JMA one-week EPS

We conducted mesoscale ensemble experiments with NHM-10 and NHM-2 using WEP perturbations as shown in Fig. 11. For detailed procedures to deduce and normalize perturbations, see Saito et al. (2010, 2011). A similar EPS system was applied to the local heavy rainfall case in Tokyo on 5 August 2008, which was brought about by sporadic scattered deep convection (Saito et al. 2017). Here, we show the forecast result by ensemble member m01, where rainfall in the southern part of Kanto was enhanced among the 11 ensemble members. Figure 13a shows the NHM-10 forecast. Areas of moderate rains (greater than 10 mm 3h$^{-1}$ (shown by yellow shading)) are somewhat enlarged in the western part of Tokyo. In its 2 km resolution downscale by NHM-2 (Fig. 13b), intense convective rains are seen around the northern part of Kanagawa Prefecture; however, false rains north of
the Kanto district are also enhanced, so the positional relationship between the frontal precipitation band and intense convective rains is different from the real situation.

4.4 Experiment with modified model physics on cloud amount evaluation

It is well known that local heavy rainfalls that occur under weak synoptic or orographic forcing are sometimes quite sensitive to small differences both in initial
and boundary conditions and model physics. Among several physical processes, urban effect and influence of aerosols on surface heating and cloud physics are of interest for severe weather over large cities, but their impact on local heavy rainfall is still not well investigated. Several TOMACS papers (e.g., Belair et al. 2018; Pereira et al. 2018; Seino et al. 2018) target the urban effect’s impact on precipitation. In this study, we tested the cloud amount evaluation scheme in NHM, which controls long- and short-wave radiation and may influence sea breezes through surface heating.

In the physical process of NHM, cloud amount is diagnosed from the relative humidity in the operational model setting. To consider the effect of subgrid condensation, partial cloudiness is estimated based on the idea of subgrid perturbation of water vapor, which is determined by the Mellor–Yamada–Nakanishi–Niino level 3 turbulent closure model (MYNN; Nakanishi and Niino 2004; Hara 2010). A probabilistic density function (PDF) is assumed to represent subgrid perturbation for a specific humidity $q_w$ (ratio of the total water amount of water vapor, cloud water, and cloud ice to moist air), and the portion of perturbed specific humidity exceeding the saturation specific humidity is regarded as the subgrid condensation (Hara 2008). In the JMA operational GSM, a constant function is assumed for its PDF, which distributes uniformly in the range from $q_w - \Delta q_w$ to $q_w + \Delta q_w$. In this case, partial cloudiness increases linearly in the above range as shown in Fig. 14a. In NHM, a Gaussian normal function with a standard deviation of $\sigma_s$ is assumed for its PDF, and the partial cloudiness increases as the accumulated function of its PDF (Fig. 14b). The magnitude of $\sigma_s$ is determined according to the deviation of the specific humidity and the potential temperature given by the MYNN scheme (Eqs. 4, 6, 9 of Hara (2008)), whereas a lower limit of $\sigma_s$ is prescribed so that a subgrid non-uniformity makes a certain partial cloudiness even if turbulence does not exist in the model atmosphere with the MYNN scheme. JMA’s operational LFM once used a value of 0.09 as its lower limit ($f_{\text{min}}$; Eq. 4.6.15 of Hara (2008)) in its early version, but the value was changed to 0.05 in August 2012 to ameliorate overestimation of cloudiness in LFM (Eito et al. 2012).

Figure 15a shows 3-h accumulated precipitation for 1500 to 1800 JST 26 August predicted by the 15-h forecast of NHM-2 from the initial time of 1800 UTC 25 August (0300 JST 26 August) corresponding to Fig. 12b, but in this case, $f_{\text{min}}$ is reduced to 0.05. Intense rains around Tokyo, which were not seen in Fig. 12b, were reproduced up to a point. The lower panels of Fig. 15 compare surface (2 m) temperatures at 1400 JST by NHM-2 with $f_{\text{min}} = 0.09$ (Fig. 15c) and $f_{\text{min}} = 0.05$ (Fig. 15d). With the original setting of $f_{\text{min}} = 0.09$, areas of surface temperature over 30°C were confined to narrow regions at the middle of the Boso Peninsula and the eastern part of Kanagawa Prefecture, which is very different from the day’s observed surface temperature (Fig. 10). When $f_{\text{min}}$ is reduced to 0.05, the surface temperatures around Tokyo increased by about 1°C, and the areas over 30°C are spread to wider regions over the Tokyo metropolitan area. This increase in surface temperature is due to the increase of short wave radiation caused by reduced cloudiness in the model with a smaller $f_{\text{min}}$. The temperature increase also intensifies the sea breezes by enhancing the contrast of the sea surface temperatures, which changes the position of the surface convergence.

Figure 15b shows 3-h accumulated precipitation from the ensemble member m01 with $f_{\text{min}} = 0.05$. Compared with the same member in WEP EPS (Fig. 13b) using the original setting of $f_{\text{min}}$, areas of intense
rains became wider, but the positions shifted slightly northward to the Saitama Prefecture. Furthermore, the false precipitation areas over Hokuriku district and the northern part of the Kanto Plain are also enhanced. The change of $f_{\text{min}}$ improved the forecast for the control run, but did not necessarily improve the forecast for the ensemble member that showed the best performance in the original model setting.

4.5 Ensemble forecast using the mesoscale singular vector

a. Mesoscale singular vector

The mesoscale ensemble forecast described in the previous subsections used forecast perturbations from JMA’s WEP EPS for the initial and lateral boundary perturbations, as in Saito et al. (2010) and Duc et al. (2013). The perturbations of WEP EPS were given by the relatively low-resolution (T213) global model
The MSV method that we used in this study was originally developed by Kunii (2010). It computes singular vectors from linear tangent and adjoint models of the JMA nonhydrostatic model-dimensional variational data assimilation system (JNoVA; Honda et al. 2005; Honda and Sawada 2008) using the Lanczos method (Simon 1984). We used the following moist total energy (TE) norm:

\[
TE = \int \int \frac{1}{2} \left( u^2 + v^2 + w^2 + w_v \rho_c (\theta^t)^2 \right) dSdz + RT \left( \frac{p^t}{p} \right)^2 + \frac{L}{c_p T_q} q'^2 dz, \tag{1}
\]

where \( \rho \) is the density; \( u, v, \) and \( w \) are the wind speeds; \( \theta, p, \) and \( q \) are the potential temperature, pressure, and specific humidity; and \( cp \) and \( R \) are the specific heat for constant pressure and the gas constant. \( \Theta = 300 \) K, \( T = 300 \) K, and \( p = 1000 \) hPa are the reference values of potential temperature, temperature, and pressure, respectively. \( R = 287.04 \) J Kg\(^{-1}\) K\(^{-1}\) is the gas constant, \( L = 2.51 \times 10^6 \) J Kg\(^{-1}\) is the latent heat constant, and \( w_v = 3.0 \) and \( w_q = 0.5 \) are the weights of the terms of the potential temperature and the mixing ratio of water vapor, individually. In this study, we set the target region to compute singular vectors for central Japan (135.0°–142.5°E, 33.0°–38.0°N; the rectangular area shown by broken lines in Fig. 17), and five singular vectors at 1200 UTC 25 August 2011 were computed with a 40-km horizontal resolution, 40 levels, and 15-h optimization periods. Then, we created 10 initial perturbations from five positive–negative pairs of MSVs.

**b. Results of EPS**

Figures 16a and 16b show 3-h accumulated precipitation for 1500–1800 JST 26 August predicted by NHM-10 and NHM-2 using the MSV method. Figures 16a and 16b, respectively, correspond to Figs. 12 and 13. Here, f\(_{\text{min}}\) is reduced to 0.05, and the forecasts by ensemble member p04 of the MSV EPS are shown. Compared with the WEP ensemble forecasts (Figs. 13a, 15b), rains over Tokyo and Kanagawa Prefecture are further intensified. Positions of convective rain cells predicted by NHM-2 (Fig. 16b) are shifted southward compared with Fig. 15b, and the positional lag against observations (Fig. 8a) was significantly reduced. Another improvement from this forecast is that the false precipitation over Hokuriku district and the northern part of Kanto district seen in Fig. 15b is not present in Fig. 16b.

The lower panels of Fig. 16 compare the horizontal distribution of equivalent potential temperatures and horizontal winds at the 900 hPa level in the initial conditions of NHM-2 for the control run (Fig. 16c) and in member p04 of the MSV EPS (Fig. 16d). In Fig. 16d, the equivalent potential temperatures at the windward side (southern part of the Shizuoka Prefecture and off the southern coast) are increased.

Figure 17 shows initial perturbations of the potential temperature and water vapor of MSV EPS member p04. In the potential temperature perturbations (Fig. 17a), areas of positive perturbation are seen from the south coast of the Shizuoka Prefecture to Kinki district. On the other hand, a weak negative perturbation area is seen from northern Kanto to the coastal area facing the Sea of Japan (Hokuriku district). Water vapor perturbations (Fig. 17b) also increase the water vapor over the windward side (Shizuoka Prefecture) and decrease the water vapor over the Niigata Prefecture. These initial condition changes reduced atmospheric stability at the windward side while stabilizing the atmosphere in northern Kanto and the Hokuriku district. This contributed to an increase in intense rains over Tokyo and Kanagawa and eliminated the false precipitation over northern Kanto and Hokuriku.

**5. Simulated low-level convergence and convective initiation**

**5.1 Simulated low-level convergence and evolution of MCS**

The left panels of Fig. 18 show hourly horizontal divergence at the 1000 hPa level from 1200 JST to 1800 JST on 26 August 2011 as simulated by NHM-2 member p04 of MSV EPS. Blue in this figure indicates convergence (negative divergence). Horizontal winds at the lowest model level (20 m above ground level) and 1-h precipitation at corresponding times are shown in the right panels. Distinct convergence is seen along the sea breeze front. In sea breeze regions, narrow convergence zones also appear along the coastlines, reflecting the difference of roughness length on sea and land.

At 1200 JST (Fig. 18a), convergence zones along sea breeze fronts are seen north of Tokyo Bay, in
central Ibaraki Prefecture, and north of the Boso Peninsula. Compared with the satellite image (upper right of Fig. 9) and surface wind analysis (Fig. 10a) from the same time, sea breeze intrusion from Kashimana and resultant convergence zone propagation are somewhat delayed, and the simulated sea breeze front north of the Boso Peninsula and the associated cloud line correspond well with observations. The sea breeze from Tokyo Bay intrudes inland in the simulation, which overestimated the northward intrusion compared to observations.

After 1300 JST (Fig. 18b), the simulated sea breeze front from Kashima-nada slowly propagated westward. At 1500 JST, it reached the boundary between

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**Fig. 16.** a) and b) Same as in Fig. 13 but the lower limit of s is reduced and the forecast by member “p04” of the EPS with the mesoscale singular vector method. c) Equivalent potential temperature and horizontal winds at 900 hPa of the initial condition of NHM-2. For the case of the control run. d) Same as in c) but member “p04” of the EPS with the mesoscale singular vector method.
Ibaraki and Chiba Prefectures (Fig. 18d) and then merged with another sea breeze front from Tokyo Bay. After that (Figs. 18e, f), the two sea breezes from the east and south and the northerly ambient wind form a triple point, which triggered deep convection. At 1800 JST (Figs. 18g, n), very intense rains of more than 50 mm h\(^{-1}\) were reproduced around Tokyo, with a maximum rainfall intensity of around 100 mm h\(^{-1}\).

These simulated characteristics of the surface wind field and convection initiation, i.e., intrusion of sea breezes and westward propagation of the line-shaped low-level convergence zone at the front, the merging of the low-level convergence zones, and succeeding initiation of deep convection after the formation of the triple point, correspond well to observations, though there is a delay in the timing. The simulated low-level wind circulation from 1600 JST to 1800 JST (Figs. 18l–n) showed a cyclonic circulation formed by sea breezes from Tokyo Bay and Kashima-nada and a northerly synoptic wind. The horizontal scale of this simulated cyclonic circulation is larger than that of the meso (miso) cyclone that Saito et al. (2013) analyzed from Doppler radar radial winds, but this local circulation likely supplied positive vorticity to the MCS around this area.

5.2 Conceptual model of convection initiation

Figure 19 illustrates a conceptual model of convection initiation over the Kanto district on the day of weak northerly ambient wind in the summer. We propose this schematic chart from previous studies (Figs. 2–4), observations (Figs. 9, 10), and numerical simulation (Fig. 18) of the 26 August 2011 event, as well as findings from MCTEX (Fig. 19 of Saito (2001)). In the morning (Fig. 19a), sea breezes driven by temperature differences between the sea and land appear along the coast. One is the easterly sea breeze from Kashima-nada, and another is the southerly sea breeze from Tokyo Bay. Along the sea breeze fronts, non-precipitating shallow clouds may appear and are detected by satellite images. The sea breeze from Kashima-nada propagates westward, whereas the sea breeze from Tokyo Bay does not intrude northward if the ambient wind is northerly.

In the afternoon (Fig. 19b), the easterly sea breeze intrudes further westward and reaches the north of Tokyo. The southern part of the sea breeze front collides with another sea breeze front from a southerly sea breeze, producing a low-level convergence zone between the two sea breezes. The position of the convergence zone depends on the ambient wind direction and surface temperature distribution, as northerly ambient wind enhances the convergence zone and puts
Fig. 18.
Fig. 18. Continued.
its position near Tokyo. Deep convection is triggered by the convergence zone. For the 26 August 2011 event, low level circulation became counterclockwise because of the northerly wind west of the convergence zone.

6. Summary and concluding remarks

A local heavy rainfall of about 100 mm h$^{-1}$ occurred at Tokyo and Kanagawa Prefecture on 26 August 2011. This rain was brought by an MCS that devel-
oped south of a stationary front that slowly moved southward. Although the horizontal scale of the MCS was larger than typical sporadic isolated convection cells, JMA’s operational mesoscale model of the day failed to predict the occurrence of heavy rainfall. In the analysis using MTSAT images and dense AWS networks, surface convergence zones appeared along the sea breeze fronts from Kashima-nada and Tokyo Bay, and intrusion and merging of these two (“E-S” type) sea breezes and convergence with the weak northerly ambient wind triggered deep convection and succeeding development of the MCS.

We conducted a numerical simulation using NHM with horizontal resolutions of 10 and 2 km. When we used mesoscale 4D-VAR analysis of JMA for the initial condition, the model tended to predict intense rainfall not over Tokyo but west of the Kanagawa Prefecture. In the mesoscale ensemble forecast using perturbations from JMA’s WEP forecast, some members showed enhanced precipitation around Tokyo, but false precipitation also appeared north of the Kanto and Hokuriku districts, and the positional relationship between the precipitation band associated with the southward moving front and the MCS was different from observations.

We tested a modification of the model where the lower limit of subgrid deviation of water vapor condensation to diagnose the cloudiness (subgrid condensation) was reduced. In the modified model simulation, surface temperatures around Tokyo increased by about 1°C, and the position of high surface temperatures shifted inland. The modified model intensified precipitation around Tokyo, but false precipitation in the Hokuriku district was also enhanced, especially in the ensemble member, which brought a better forecast than the original model setting.

We also conducted ensemble prediction using a mesoscale MSV method. One of the ensemble members destabilizes the lower atmosphere on the windward side of the Kanto district and suppresses the false precipitation in the Hokuriku district, yielding a simulation result closer to observations. A simulated evolution of the sea breezes and convection initiation by NHM with a horizontal resolution of 2 km well reproduced observed characteristics, such as intrusion of the E-S-type sea breezes, propagation and merging of low-level convergence zone at the sea breeze fronts, formation of a triple point, and the succeeding development of deep convection. Northerly synoptic winds in the western part of the Kanto district and the E-S sea breezes from Kashima-nada and Tokyo Bay produced a cyclonic circulation west of Tokyo.

There are some differences between the simulated results and observations. The northward sea breeze intrusion from Tokyo Bay was too deep, the westward propagation of the sea breeze from Kashima-nada was too slow, and the timing of the succeeding convection initiation was delayed in the simulation. To ameliorate these discrepancies, it is necessary to improve the numerical model. A horizontal resolution of 2 km is not necessarily high enough to represent the evolution of the MCS, and our simulation does not consider the urban effect. Belair et al. (2018) conducted a numerical simulation of the local heavy rainfall of the same event and demonstrated the importance of horizontal resolution and the urban effect. The importance of the urban effect on local rains in the Tokyo metropolitan area was also shown by Pereira et al. (2018) and Seino et al. (2018). Urban effect heating will reduce the delay in the timing of convection initiation. Modification of cloudiness diagnostics in NHM had a clear impact on convection initiation through changes in surface temperatures around Tokyo. The impact of aerosols on short range forecasts is still arguable, but our result suggests that the interaction of aerosols and clouds strongly affect the position and timing of convection initiation.

To further improve the short range forecast, modification of the initial condition by high resolution assimilation of observed data, including the surface convergence by sea breeze propagation, is needed. There is no doubt that this event is very attractive as a target case for applying high resolution data assimilation systems. To confirm the reply on these remarks is the future subject.

**Supplement 1**

(a) Surface temperature and (b) relative humidity observed by the dense surface observation network at 1200 JST on 9 August 2009. A Barb indicates horizontal wind. Broken lines denote convergence lines. After Araki et al. (2015).

**Supplement 2**

MTSAT-1R rapid scan with wind and temperature.

**Supplement 3**

MTSAT-1R rapid scan (animation).

**Acknowledgments**

The Tokyo Metropolitan Area Convection Study (TOMACS) was conducted by cooperation of several national institutions and universities in Japan includ-
ing the National Research Institute for Earth Science and Disaster Resilience (NIED) and the Meteorological Research Institute (MRI) of the Japan Meteorological Agency (JMA). We thank Tsuyoshi Nakatani and Ryoei Misumi of NIED, and Yoshinori Shoji, Hiromu Seko and Naoko Seino of MRI, members of the TOMACS International Science Steering Committee and the Local Organizing Committee, and the World Weather Research Programme (WWRP) of the World Meteorological Organization (WMO) for their effort and support on TOMACS. Figure 5 was reproduced by the courtesy of Yoshinori Shoji.

The superimposed figures of satellite images and JMA observations in Fig. 9 were processed using the JMA’s observation data display system, and the authors are indebted to Yoshinobu Tanaka and Yoshihiko Tahara of JMA for their help. We also thank Fumiaki Fujibe of the Tokyo Metropolitan University, and Tabito Hara and Masayuki Nakagawa of the Numerical Prediction Division of JMA for their valuable comments on local circulation in the Kanto district and operational NWP models of JMA. Careful and constructive comments by two anonymous reviewers and the editor, Ryoei Misumi of NIED, significantly improved the quality of the manuscript.

In addition to TOMACS, this study was partly supported by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) through a Grant-in-Aid for Scientific Research ‘Study of optimum perturbation methods for ensemble data assimilation’ (16H04054), the HPCI Strategic Program for Innovative Research (SPIRE) Field 3 (hp150214), and the FLAGSHIP2020 project (Advancement of meteorological and global environmental predictions utilizing observational “Big Data”; hp160229, hp170246).

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